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## EVALUATION OF FUTURE JET FUEL COMBUSTION CHARACTERISTICS

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FUELS AND LUBRICATION DIVISION*

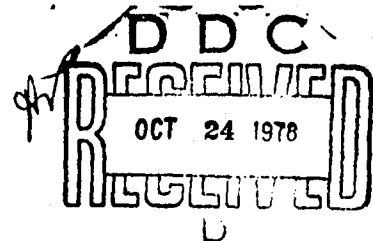
JULY 1978

TECHNICAL REPORT AFAPL-TR-77-93  
Final Report for Period July 1975 - November 1976

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This technical report has been reviewed and is approved for publication.

  
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20. Abstract

influence of hydrogen content on combustion characteristics when compared to volatility and hydrocarbon type effects. Use of the new non-dimensional liner temperature parameter has also resulted in a good correlation of a wide variety of previous combustor data involving rich combustion systems. However, comparison with data obtained using low-smoke combustor design indicated that newer designs having airblast fuel injection and leaner combustion may be much less sensitive to fuel hydrogen content. Fuel bound nitrogen-to-NO<sub>x</sub> conversion in an aircraft gas turbine combustor has been evaluated. The conversion percent was found to decrease with increasing fuel nitrogen content or with increasing combustor inlet temperature. The effectiveness of a smoke abatement fuel additive and a lean combustor primary zone have also been investigated. The additive reduced smoke emission but not liner temperature while the lean primary zone resulted in lower liner temperatures but no significant smoke emission decrease.

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FOREWORD

This report describes an in-house effort conducted by personnel of the Fuels Branch (SFF), Fuels and Lubrication Division (SF), Air Force Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, under Project 3048, "Fuels, Lubrication, and Fire Protection," Task 304805, "Aero Propulsion Fuels," Work Unit 30480569, "Alternate Fuel Combustion Investigation."

The work reported herein was performed during the period 1 July 1975 to 30 November 1976 under the direction of W. S. Blazowski. L. P. Tackett and F. S. Farenbruck were the engineering personnel responsible for all testing reported herein except for Phase II of the Investigation of Hydrogen Content Variations. T. A. Jackson was the engineer in charge of this test phase.

Numerous individuals were involved in supporting this test program. The assistance of members of the Technical Facilities Division in preparing test fuels and operating the support facilities and test hardware is gratefully acknowledged. The cooperation of the Monsanto Research Laboratory, the Air Force Logistics Command Aerospace Fuels Laboratory (SFQLA), and the Air Force Materials Laboratory in analyzing test fuels used in this program is also gratefully acknowledged. In addition, specific thanks is extended to 1st Lt J. W. Marzeski and Mr. R. Bradley for their assistance as test engineers during this program.

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## SECTION I

### INTRODUCTION/BACKGROUND

#### Problem Definition

Between 1973 and the present time, the cost and availability of aircraft jet fuels have drastically changed. Per-gallon jet fuel costs have more than tripled for both commercial and military consumers. In addition, fuel procurement actions have encountered difficulties in obtaining desired quantities of fuel, even though significantly reduced from 1972 consumption levels. These developments have encouraged initial examinations of the feasibility of producing jet fuels from non-petroleum resources (1-4).

Although economics and supply are primarily responsible for this recent interest in new fuel sources, projections of available world-wide petroleum resources also indicate the necessity for seeking new means of obtaining jet fuel. Regardless of current problems, the dependence on petroleum as the primary source of jet fuel can be expected to cease sometime within the next half century (4-5).

If the general nature of future aircraft (size, weight, flight speed, etc.) is to remain similar to today's designs, liquid hydrocarbons can be expected to continue as the primary propulsion fuel. Liquified hydrogen and methane have been extensively studied as alternatives but seem to be practical only for very large aircraft. The basic-non-petroleum resources from which future liquid hydrocarbon synfuels might be produced are numerous. They range from the more familiar energy sources of coal, oil shale, and tar sands to possible future organic materials derived from energy farming. Experience to date indicates that basic synthetic crudes, especially those produced from coal, will be appreciably different from petroleum crude.

Because of the global nature of aircraft operations, jet fuels of the future are likely to be produced from a combination of these basic sources. Production of fuels from blends of synthetic crudes and natural crudes may also be expected. In light of the wide variations in materials from which worldwide jet fuel production can draw, it is anticipated that economics and availability will dictate the acceptance of future fuels with properties other than those of currently-used JP-4, JP-5, and Jet A. Much additional technical information will be required to identify the fuel characteristics which provide the optimum solution to the following objectives:

- a) allow usage of key worldwide resources to assure availability
- b) minimize the total cost of aircraft system operation
- c) avoid sacrifice of engine performance, flight safety, or environmental impact.

A complex program is necessary to establish the information base from which future fuel specifications can be made. Figure 1 depicts the overall nature of the required effort. Fuel processing technology will naturally be of primary importance to per-gallon fuel costs. The impact of reduced levels of refining (lower fuel costs) on all aircraft system components must be determined. These include fuel system (pumps, filters, heat exchangers, seals, etc.), and airframe (fuel tank size and design, impact on range, etc.) considerations as well as main burner and afterburner impacts. In addition, handling difficulties (fuel toxicity) and environmental impact (exhaust emissions) require evaluation. The overall program must be integrated by a system optimization study intended to identify the best solution to the stated objectives.

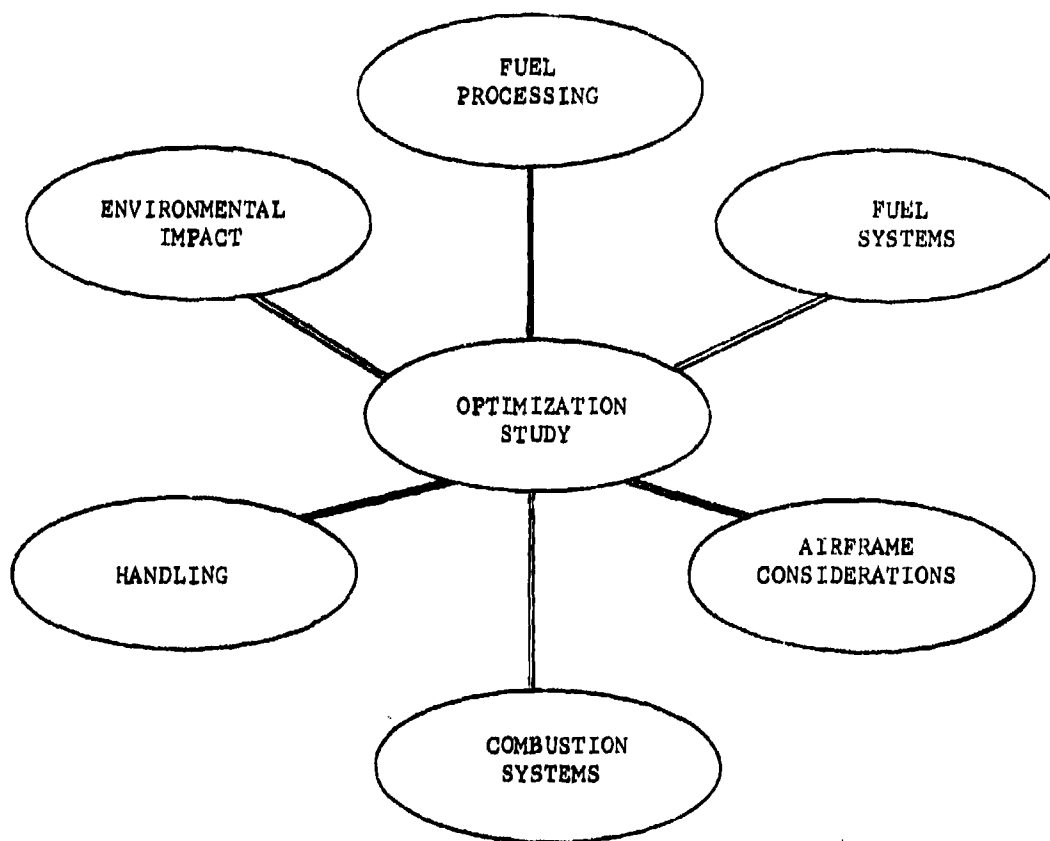


Figure 1. Overall Scheme for Alternate Jet Fuel Development Program

Fuel Effects on Combustion Systems

This report concerns the impact of varying key fuel properties on aircraft turbine engine combustion systems. The long term goal of this and similar programs is to better specify jet fuels to help in optimizing the total aircraft/engine/fuel Life Cycle Cost (LCC). Fuel properties which may be expected to vary and which would potentially affect combustion system/engine performance are fuel hydrogen content, fuel nitrogen, volatility, viscosity, olefinic content, sulfur, and trace metal content.

Hydrogen content in future crudes will be the most significant parameter affecting cost and availability of jet fuel. Reduction in crude hydrogen content is due to increased concentrations of aromatic-type hydrocarbons. These may be either single ring or polycyclic in structure, it would be desirable from the processing cost standpoint to permit the use of jet fuels with lower hydrogen content (higher aromatic content).

Experience has shown that decreased hydrogen content significantly influences the fuel pyrolysis process in a manner which results in increased rates of carbon particle formation. For example, Wright (6) has demonstrated that the equivalence ratio for incipient soot formation in a well-stirred reactor is a strong function of fuel hydrogen content. Smoke emissions resulting from this change can substantially influence vulnerability in the case of military aircraft, as well as cause environmentally related smoke regulations to be violated. In addition to increased smoke emission, the particulates are responsible for the formation of a luminous flame within the combustor. Radiation from these particles becomes the predominant mode of heat transfer. The increased radiative loading on combustor liners which results from decreased hydrogen content can be substantial. Increases

exceeding 100°C will be reported later in this document. These variations in liner temperature translate into decreases in hardware life and reliability.

Future crude sources can also be expected to contain greater quantities of bound nitrogen. While normal petroleum-derived jet fuels have near-zero fuel nitrogen (<20 ppmw), oil shale jet fuels have been produced with levels up to 0.1%, or 1000 ppmw (3). Previous efforts have indicated that 50-100% of fuel-bound nitrogen is converted into oxides of nitrogen ( $\text{NO}_x$ )\* during the combustion process (7). At a 100% conversion level, 0.1% nitrogen in the fuel converts to an increased  $\text{NO}_x$  emission index\*\* of 3.3. While this is not a large increase over typical high power operating values of current engines (15-40 gm  $\text{NO}_2$ /kg fuel), it does represent a substantial increase at idle operation where  $\text{NO}_x$  emission index is usually less than 5. Further, the fuel-bound nitrogen contribution to  $\text{NO}_x$  emission will be substantial even at takeoff conditions in future engines having reduced  $\text{NO}_x$  emission levels ( $\approx 10$  gm  $\text{NO}_2$ /kg fuel) to meet current pollutant emission regulations. Considering that  $\text{NO}_x$  emissions are the most difficult pollutant to control, the fuel bound nitrogen contribution to  $\text{NO}_x$  emission must be minimized.

Volatility affects the rate at which liquid fuel introduced into the combustor can vaporize. Since important heat release processes do not occur until gas phase reactions take place, reduction of volatility shortens the time within the combustion system where chemical reaction might occur. In the aircraft engine, this can manifest itself as difficulty in ground or altitude ignition capability, loss of combustor stability, increased emissions of carbon monoxide (CO) and hydrocarbons (HC), and the associated loss in

\*  $\text{NO}_x$  is the symbol given to represent the collective emission of NO &  $\text{NO}_2$ .

\*\* Emission index expresses pollutant emission as gm pollutant per kg of fuel burned. In the case of  $\text{NO}_x$  emission, both NO and  $\text{NO}_2$  are taken at the molecular weight of  $\text{NO}_2$  for this calculation.

combustion efficiency. Moreover, carbon particle formation is aided by the formation and maintenance of rich fuel-air pockets in the hot combustion zone. Low volatility allows locally rich volumes to persist because of the reduced vaporization rate. Again, increased particulates can cause additional radiative loading to combustor liners and more substantial smoke emissions.

The desired formation of a finely dispersed spray of small fuel droplets is adversely affected by increased viscosity. Consequently, the shortened time for gas phase combustion reactions and prolonging of rich fuel-air pockets experienced with low volatility can also occur with increased viscosity. The ignition, stability, emissions, and smoke problems previously mentioned also increase for higher viscosity fuels.

Olefinic content is known to be important to considerations of fuel thermal stability and storage stability. In addition to considerations of fouling oil-fuel heat exchangers and filters, excessive olefinic content can cause fuel metering valves and fuel nozzles to plug. But, no negative effect of fuel olefinic content on gas phase combustion processes would be expected.

Both sulfur and trace metals are at very low concentrations in current jet fuels. Sulfur is typically less than 0.1% because the petroleum fraction used for jet fuel production is nearly void of sulfur-containing compounds. Although syncrudes from coal or oil shale would be expected to contain higher sulfur levels, it is not likely that the current specification limit of 0.4% would be exceeded with the processed jet fuel. Because of the way in which future jet fuels are expected to be produced (2), trace metals are expected to continue to be present at low concentrations (less than 1 ppmw).

Should higher levels appear possible, the serious consequences (especially deleterious effects on expensive turbine blades) may justify additional expense for removal.

#### Minimizing Combustion System Impact

Approaches to widening the fuel tolerance range of gas turbine combustion systems in order to reduce aircraft system LCC must be developed. Among the methods investigated in this study are fuel additives and combustion system redesign. In each case, the technique would seek to accommodate lower hydrogen content fuels without combustor liner temperature, smoke, or  $\text{NO}_x$  emission increases while maintaining the customary level of combustion system performance.

A number of smoke abatement fuel additives have been evaluated in aircraft gas turbine engines. Effective additives contain an active metal usually from the transition metal group (Mn, Ba, Ca, Ni). These compounds are blended with the fuel to metal concentrations of 50-100 ppmw for significant smoke reduction. As applied to the question of future aircraft systems, the effectiveness of these additives with low hydrogen content fuels and the possibility of reducing the sensitivity of combustor liner temperature to hydrogen content with the additives remained undetermined. Previous studies have indicated that the additives do not affect combustion zone radiation (8). Also, a previous AFAPL program (9) had indicated some reduction of  $\text{NO}_x$  by the same additive compounds used for smoke abatement. Relatively large additive concentrations (1000 ppmw of metal) were required for reductions of 10%. Unfortunately, the testing was limited to combustor inlet temperatures of 500°K, significantly under the values of practical interest (up to 850°K). The possibility



of increased additive effectiveness at higher combustion temperature remained. These questions are addressed in this report.

It should be noted that recent experience has indicated that continuous engine operation with these additives is not desirable as they adversely affect the hot section downstream of the combustor. Therefore, work in this area beyond that covered by this report is not anticipated.

Combustion system design changes which will be employed to accommodate reduced hydrogen content fuels center around leaner combustion. Low smoke combustor designs, already having leaner primary zones (10), will be shown to be less sensitive to fuel hydrogen content. More advanced designs have attempted to achieve premixed, prevaporized combustor zones and are expected to allow even further reduction in fuel sensitivity. Preliminary testing of a number of combustors developed in the NASA Experimental Clean Combustor Program (10-11) has indicated that these designs function nearly independent of fuel type. This report will cover an investigation conducted with a T56 combustor modified to achieve a lean primary combustion zone by redistributing the dilution air.

#### Present Program Objectives

This report addresses the aspect of the overall alternate fuel program described in Figure 1 which deals with fuel property effects on engine combustion systems, specifically main burners. All testing was conducted in-house at AFAPL during 1975 and 1976. The purpose of the subject study were: a) to systematically evaluate the impact of lower fuel hydrogen content on combustor liner temperature, smoke, and gaseous exhaust emissions, b) to develop improved correlations for the effects of lower hydrogen content, c) to evaluate fuel bound nitrogen-NO<sub>x</sub> conversion in an aircraft gas turbine combustion system, d) to

3  
determine the effectiveness of a fuel additive in reducing the combustion system impact of a simulated jet synfuel, and e) to evaluate a lean primary zone combustor. Nearly all results reported herein involved fuel blends which were intended to simulate fuels available from non-petroleum resources. AFAPL testing of actual synfuels during 1975 has been reported in Reference 12.

## SECTION II

### EXPERIMENTAL

All testing was performed in the AFAPL combustor rig facility shown in Figure 2. Air supplied by a series of three Ingersol Rand compressors was heated to temperatures simulating various conditions of compressor discharge by passing through an unvitiated, gas-fired furnace. The system was capable of supplying 3.4 kg/sec of air at 18 atm pressure and temperatures up to 840°K. Accurate control of combustor air flow and pressure was accomplished by an automatic air bleed control valve and an exhaust plug operated from the control room. A 2-inch throat diameter venturi was used to measure air flow, and fuel flow was determined using a turbine flow meter. All inlet and exhaust temperatures were measured with chromel-alumel thermocouples.

T56 Series III single combustors were utilized in this study. Six combustors of the type tested (see Figure 3) are arranged in annular fashion in the T56 engine which is used in the C-130 aircraft. Although the T56 combustor has specific operating conditions of inlet temperature, air flow rate, fuel-air ratio, and pressure, the combustor was operated at conditions simulating a wide variety of engines. Air flow at all conditions was scaled to simulate a constant compressor discharge Mach number. In effect, this allows air mass flow to be scaled as  $PT^{-1/2}$ . Considering facility limitations, T56 combustor design requirements, and the above described scaling law, the conditions listed in Table 1 were selected as the basis for the tests conducted. Two engine types (high and low pressure ratio) and two engine conditions (idle and subsonic cruise) were simulated. An additional condition corresponding to supersonic cruise was utilized in a limited number of tests.

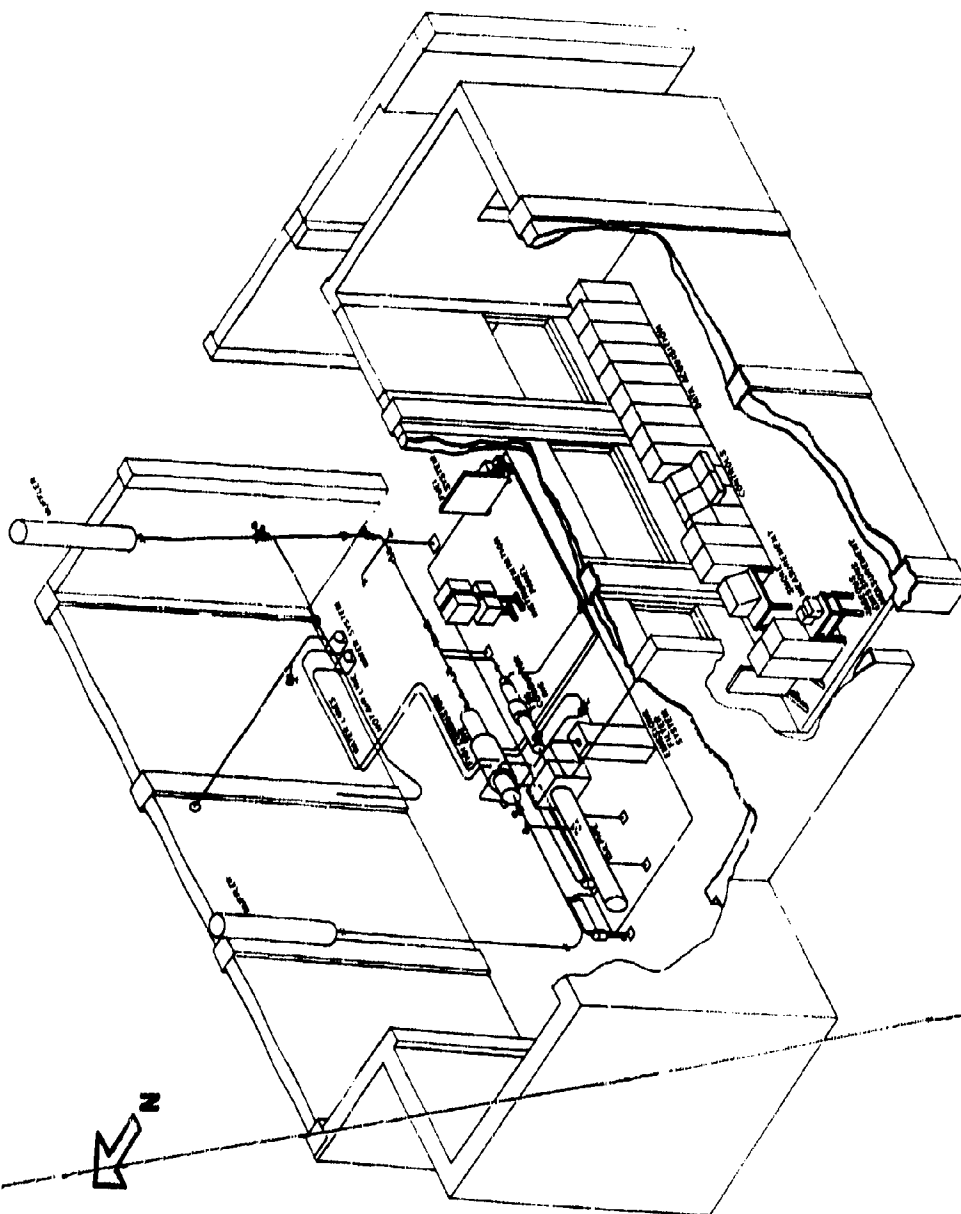


FIGURE 2. AFAPL Combustor Rig Facility

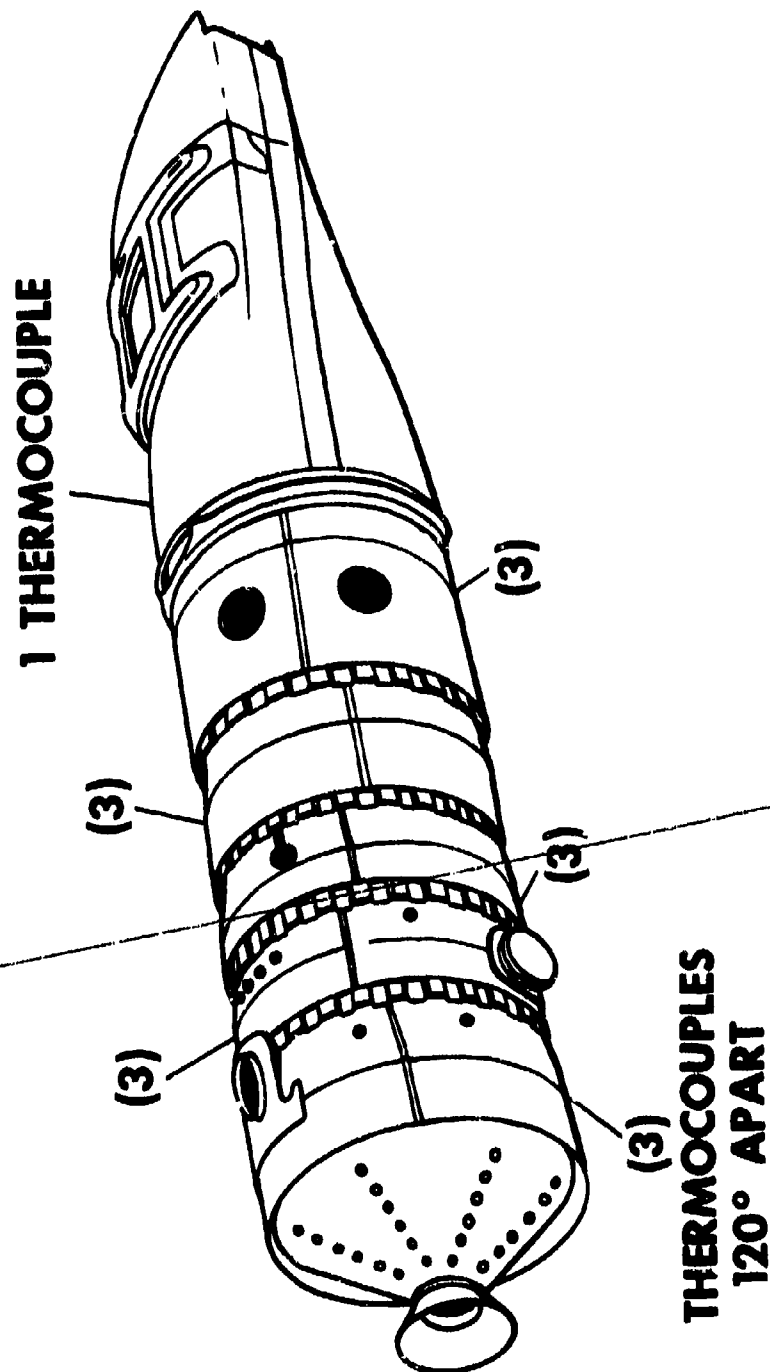


FIGURE 3. T56 Single Combustor

TABLE 1  
COMBUSTOR RIG TEST CONDITIONS

<u>Condition</u>	<u>Inlet Pressure (atm)</u>	<u>Air Mass Flow (kg/sec)</u>	<u>Inlet Temperature (°K)</u>	<u>Exit Temperature*</u> (°K)
Low Pressure Ratio Idle	2.5	0.84	394	674
High Pressure Ratio Idle	4.5	1.36	478	758
Low Pressure Ratio Cruise	7.8	2.00	644	1200
High Pressure Ratio Cruise	8.5	2.04	756	1200
Supersonic Cruise	6.1	1.41	838	1200

\* Based on 100% Combustion Efficiency

The combustor liner was instrumented with sixteen chromel-alumel thermocouples in the arrangement shown in Figure 3. These direct measurements provided the only means of determining the effects of increased combustion zone radiation (actual radiation measurements were not accomplished). Exhaust smoke and gaseous emission instruments were supplied with exhaust gases from a sampling probe located approximately one meter from the combustor exit. This distance allowed sufficient mixing to eliminate combustor exit concentration non-uniformities. The gas sample from the probe passed through a heated line in accordance with accepted measurement practice (13, 14). Exhaust composition was determined by the following methods: nondispersive infrared detection for carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>), flame ionization sensing for total hydrocarbons (HC), chemiluminescence for oxides of nitrogen (NO<sub>x</sub>), and SAE Smoke Number measurement by the procedures of Reference 13. The actual instrumentation utilized is listed in Table 2. CO<sub>2</sub>, CO, and hydrocarbon compositions were used to calculate a fuel-air ratio which was compared with the value computed from directly measured fuel and air flow rates to verify acquisition of a representative sample. The criteria for data acceptance was agreement of the two fuel-air ratio values to within  $\pm 15\%$ .

TABLE 2

EXHAUST GAS ANALYSIS INSTRUMENTATION

<u>Emission Species</u>	<u>Type Instrument</u>	<u>Manufacturer/Model</u>	<u>Ranges PPMV or %</u>
CO	NDIR	Beckman/315B	0-400,1000,2000
CO <sub>2</sub>	NDIR	Beckman/315B	0-2.5, 10%
NO/NO <sub>x</sub>	Chemiluminescence	Thermo-Electron/10A	0-2.5,10,25,100,250,1000,2500,10000
THC	Flame Ionization (Heated)	Beckman/402	0-5,25,50,250,500,2500,5000

Investigation of Hydrogen Content Variations

The first phase of testing lower hydrogen content fuels was intended to establish the impact on the operating characteristics of the T56 combustor. Test fuels were formulated by blending xylene with JP-4 or JP-5. Gaseous emissions, smoke, and combustor liner temperature data were acquired at idle and subsonic cruise operating conditions. The correlation established between combustor liner temperature and hydrogen content was surprisingly good. A second phase of testing was intended to examine the universality of the correlation initially established. Fuels tested were selected to expand the range of hydrogen content previously examined and to study various hydrocarbon types as blending agents. Combustor liner temperature at the two subsonic cruise conditions was the primary factor investigated during this phase of testing. The two test phases are described separately below.

Phase I: Nine fuels were studied to determine the effects of lower hydrogen content on main combustion systems. Three of the fuels were prepared at the AFAPL by the addition of xylene to JP-4 to increase aromatic content to

25, 35, and 45 percent by volume. This corresponded to hydrogen contents of 13.9 (Fuel A), 13.3 (Fuel B), and 12.6 (Fuel C) weight percent. The largest amount of testing was accomplished using these three fuels. The second three fuels, also prepared at AFAPL, were composed of blends of xylene with JP-5. These results were acquired to identify the influence of fuel volatility on the relationship between combustion characteristics and hydrogen content. Blending was performed for aromatic contents of 25, 35, and 45 percent by volume, which corresponds to hydrogen contents of 13.3, 12.8, and 12.3 percent by weight. These fuels were coded D, E, and F.

Two other fuels were obtained from NASA. These were similar to test fuels which had previously been studied in the contractual Experimental Clean Combustor Programs (10,11). They were prepared by blending either a mixture of single-ring aromatics or naphthalene with Jet A and were coded G and H. Finally, a Jet A fuel prepared by Shell Canada from tar sands (Fuel I) was studied. This synfuel is considered to be a naturally occurring lower hydrogen content fuel (13.29%). This is the only synfuel to be discussed herein, as the test results have not been reported elsewhere.

Fuels A thru C and G thru I were sent to three laboratories for analysis. They included Monsanto Research Laboratories (Dayton, OH), Air Force Logistics Command (AFLC) Fuels Laboratory (Wright-Patterson AFB), and the Air Force Materials Laboratory (AFML, Wright-Patterson AFB). The AFLC laboratory performed a complete specification analysis. Monsanto and AFML accomplished an elemental analysis. All results are shown in Table 3.

Combustor rig testing was accomplished for both idle and subsonic cruise conditions for each of these nine fuels. Combustor liner temperature, exhaust emissions, and smoke were all recorded. Each data point was repeated two



TABLE 3. ANALYSIS OF LOWER HYDROGEN CONTENT FUELS TESTED

	A		B		C		D		E		F		G		H		I	
	JP-4	25% Aromatic JP-4	35% Aromatic JP-4	45% Aromatic JP-4	JP-4	JP-5	25% Aromatic JP-5	35% Aromatic JP-5	45% Aromatic JP-5	JP-5	45% Aromatic JP-5	JP-5	High Aromatic	High Aromatic	High Naphthalene	High Naphthalene	Shell Canada	Shell Canada
Aromatics (Vol %)	9.4	24.8	35.4	44.9	15.2	25	35	45	53.2	34.7	20.1	147	145	147	145	147	147	147
Dicfins (Vol %)	1.2	0.8	1.1	.9	1.8				.9	1.3	0.7	175	188	188	175	175	175	175
Sulfur Perceptim (Wt %)	0.000	0.000	0.000	0.000					0.000	0.000	0.000	188	201	201	188	188	188	188
Sulfur Total (Wt %)	0.030	0.028	0.023	0.023								216	216	216	216	216	216	216
Distillation												241	241	241	241	241	241	241
Initial bp (°C)	61	55	67	71	182							251	251	251	251	251	251	251
10% Rec (°C)	99	99	108	113	197							282	282	282	282	282	282	282
20% Rec (°C)	113	114	121	126	203							39.1	39.1	39.1	39.1	39.1	39.1	39.1
50% Rec (°C)	144	144	149	149	218							8 -40	8 -40	8 -40	8 -40	8 -40	8 -40	8 -40
90% Rec (°C)	224	219	215	205	246							3191	3191	3191	3191	3191	3191	3191
Final BP (°C)	247	247	243	246	42.6							10.174	10.174	10.174	10.174	10.174	10.174	10.174
Gravity API	56.0	50.9	48.2	45.6	B -46													
Vapor Pressure (atm)	0.156	0.143	0.129	0.102														
Freeze Pt. (°C)	B -57	B -57	B -57	B -57														
Aciline Gravity Product	7933.	5803.	4483.	3283.														
Heating Value Calculated (Cal/gm)	10.451	10.328	10.250	10.179														
C % WT	85.14	86.27	86.77	86.88	13.80	13.3	12.8	12.3	87.80	87.56	85.77							
H % WT	14.49	13.9	13.3	12.6					11.93	12.26	13.29							
N % WT	0.003	0.012	0.015	0.006					0.0	0.0	0.0							
O % WT	0.11	0.20	0.1	0.03					0.28	0.23	0.24							
S % WT	0.015	0.015	0.019	0.014														

times. Experiments were conducted over a one-year time period and, because of decreased durability due to the higher temperature operating conditions, it was necessary to replace the combustor a number of times.

Between each set of test fuel data points, the rig was operated with a typical JP-4 to assure repeatability and proper operation of all measurement equipment. Characteristics of the JP-4 used for this purpose (Fuel AFFB-73-16) are also shown in Table 3.

Phase II: Ten test fuels were studied in this phase of the investigation. The first three of these were intended to expand the range of hydrogen content previously investigated. Fuels J, K, and L had hydrogen contents of 9.9, 10.5, and 11.5%. The 9.9% hydrogen content fuel was 100% xylene and the other fuels were blends of xylene with JP-4. Two additional fuels were within the range of hydrogen content studied in Phase I and were intended to examine the reproducibility of results. These Fuels, M and N, had hydrogen contents of 12.5 and 13.5%. To examine the combustor liner temperature correlation for hydrogen contents greater than that of JP-4, fuels O and P were tested. These were a JP-4/iso-octane (2-2-4 trimethylpentane) blend having 15.2 hydrogen and pure iso-octane having 15.9% hydrogen.

Examination of the influence of hydrocarbon type on the correlation was undertaken using fuels Q, R, and S. Fuel Q was a blend of iso-octane and decalin (decahydronaphthalene) having a hydrogen content identical to that of the baseline JP-4. Fuel R was a blend of naphthalene, a completely unsaturated double ring aromatic, with JP-4 and xylene. This fuel, blended with a one-to-one naphthalene/xylene weight ratio, had a hydrogen content of 12.5. Initial testing of this blend was accomplished during the summer months and no

noticeable problems were encountered. When the fuel was re-tested in the colder months of the 1976 autumn, however, the cool weather prevented the naphthalene from remaining in solution. Fuel S was a blend of tetralin (tetrahydronaphthalene) in JP-4 having a hydrogen content of 12.5%.

Phase II combustor rig testing included the two cruise operating conditions. Measurements were taken of combustor liner temperature only. Smoke measurements were attempted but excessive smoke generated by fuel J in the first test series of this phase rendered the smoke equipment temporarily inoperable. The decision was made to continue testing without smoke measurements. The severe operating conditions encountered during the test program caused the combustor to require re-instrumentation. While this combustor can was being re-instrumented, a different T56 combustor was used to generate additional data on four of the test fuels. This combustor was somewhat different from the initial hardware in that it had a richer primary zone. The results of this test series will also be reported.

A thorough analysis of each test fuel was not considered necessary in Phase II. All blending components were pure hydrocarbons or JP-4 (extensively analyzed in Phase I, see Table 3). Further, experience gained in Phase I fuel blending has made the overall blending operation a matter of routine. Hydrogen content of the test fuel blends were checked at the AFAPL chemistry laboratory using an HCN Elemental Analyser. The results indicate the success of the blending operation. Table 4 summarizes the test fuels utilized in Phase II.

Between each set of test fuel data points, the rig was operated with a typical JP-4 to assure repeatability and proper operation of all measurement equipment and to provide a baseline. For test convenience, a facility source of JP-4 was used for this purpose. This JP-4 was not from the same

TABLE 4  
SUMMARY OF CHARACTERISTICS FOR FUELS  
USED IN HYDROGEN CONTENT VARIATION

	<u>Fuel</u>	<u>Composition</u>	<u>Hydrogen Content (WT %)</u>
Phase I:	A	JP-4/Xylene	13.9
	B	JP-4/Xylene	13.3
	C	JP-4/Xylene	12.6
	D	JP-5/Xylene	13.3
	E	JP-5/Xylene	12.8
	F	JP-5/Xylene	12.3
	G	Jet A/Single Ring Aromatic	11.9
	H	Jet A/Napthalene	12.3
	I	Tar Sands Jet A	13.3
Phase II:	J	Xylene	9.9
	K	JP-4/Xylene	10.5
	L	JP-4/Xylene	11.5
	M	JP-4/Xylene	12.5
	N	JP-4/Xylene	13.5
	O	JP-4/Iso-Octane	15.2
	P	Iso-Octane	15.9
	Q	Iso-Octane/Decalin	14.5
	R	JP-4/Napthalene/Xylene	12.5
	S	JP-4/Tetralin	12.5
JP-4	Baseline	Code AFTB-73-16	14.5
JP-5	Baseline		13.8

source as that used in blending (Fuel AFTB-73-16). However, the blending JP-4 was tested against the facility JP-4 in the T56 test rig to check for discrepancies. The fuels behaved identically in the rig according to all instrumentations and the facility JP-4 was there after considered an acceptable baseline for this test program.

#### Fuel Bound Nitrogen Investigation

This testing was conducted to examine the effects of increased fuel nitrogen content on NO<sub>x</sub> emissions in an aircraft-type gas turbine combustor. The fuels were prepared at AFAPL by addition of pyridine to JP-4 to raise fuel

nitrogen content to 1.0, 0.3, or 0.1% by weight. These fuels were coded T, U, and V. Because of the low hydrogen content of pyridine, xylene was also blended into these fuels in amounts which maintained an approximately constant hydrogen content (15.4%).

Table 5 lists the analysis of these fuels along with the characteristics of the baseline JP-4 used during this time period. Attempts to obtain an analysis of nitrogen content through the previously mentioned organizations resulted in failure; neither agreement between organizations nor results consistent with the known blending amounts were obtained. Consequently, Mr. Paul Hayes of AFAPL/SFF was asked to perform liquid chromatographic analysis of the test fuels. The task was simplified by knowing in advance that the predominant form of fuel nitrogen was pyridine. His nitrogen content results, reported in Table 5, agreed very well with that expected from the blended quantities.

All fuels were tested at each of the combustor operating conditions, including supersonic cruise. Three data points were obtained at each combination of fuel and operating condition. The data of primary interest were the NO<sub>x</sub> emission for the high nitrogen content fuel versus that for the typical JP-4 (which had very little bound nitrogen, 30 ppm) at the same operating condition.

#### Fuel Additive Testing

Due to a limited amount of test time, it was only possible to evaluate one fuel additive during this program. The additive selected was methyl cyclopentadienyl manganese tricarbonyl, a liquid compound suitable for blending with distillate fuels. This compound is commercially available through Ethyl

TABLE 5. High Fuel Nitrogen Test Fuels

	JP-4 Baseline	T 1.0% Nitrogen	U .3% Nitrogen	V .1% Nitrogen
Aromatics (Vol %)	9.4	20.9	23.2	21.9
Olefins (Vol %)	1.2	1.9	2.3	2.1
Sulfur Mercaptan (wt %)	0.000	0.000	0.000	0.000
Sulfur Total (wt %)	0.030	.018	.045	.024
Distillation				
Initial BP (°C)	61	64	68	62
10% Rec (°C)	99	101	104	99
20% Rec (°C)	110	112	116	111
50% Rec (°C)	144	140	145	143
90% Rec (°C)	224	214	219	213
Final BP (°C)	247	250	248	244
Gravity API	56.0	49.9	50.7	50.8
Vapor Pressure (atm)	0.156	0.136	0.136	0.123
Freeze Point (°C)	B-57	--	--	--
Aniline Gravity Product	7903	5888	5831	5893
Heating Value Calculated (cal/gm)	10,451	10,333	10,329	10,333
Smoke Point		54.1	54.6	55.0
C wt%	85.14	84.90	86.00	84.65
H wt%	14.49	13.43	13.64	13.12
N wt%	0.003	1.0	0.3	0.1
S wt%	0.011	0.016	0.014	0.015
O wt%	0.015	0.06	0.12	0.12

Corporation as CI-2. It is known and marketed for its ability to act as a smoke abatement additive in gas turbine engines. As previously noted, manganese has also been indicated as having some NO<sub>x</sub> reduction potential (9).

The additive was blended with typical JP-4 and with Fuel B in amounts resulting in manganese concentrations of 50, 100, and 300 ppmw. These fuels are coded B-1, B-2, and B-3. The fuels were examined in the T56 combustor rig at the low and high pressure cruise conditions previously described. Smoke and combustor liner temperature data were of paramount interest to this testing.

An additional fuel blend was used to determine the effects of CI-2 on NO<sub>x</sub> emissions in the presence of high fuel bound nitrogen. JP-4 was doped with xylene and pyridine to achieve a final fuel blend of JP-4/35% aromatics/0.3% nitrogen. This was a simulation of Fuel B with 0.3% nitrogen. This blend was then treated with CI-2 to achieve 50, 100, and 300 ppmw manganese. These fuels were coded B-4, B-5, and B-6. The high mach cruise condition was examined using this fuel in addition to the low and high pressure subsonic cruise conditions. Naturally, the primary measurement in this test was NO<sub>x</sub> emission.

#### Lean Combustor Investigations

A standard T56 combustor was made to operate with a leaner primary zone than normal by increasing the diameter of primary zone air inlet holes while simultaneously reducing the size of secondary air inlet holes. This was accomplished in a manner which allowed the total combustor pressure drop characteristics to remain unchanged. The net effect of this modification was to cause additional air to enter the primary zone, resulting in a 28% leaner primary zone. Figure 4 shows the modified combustor.

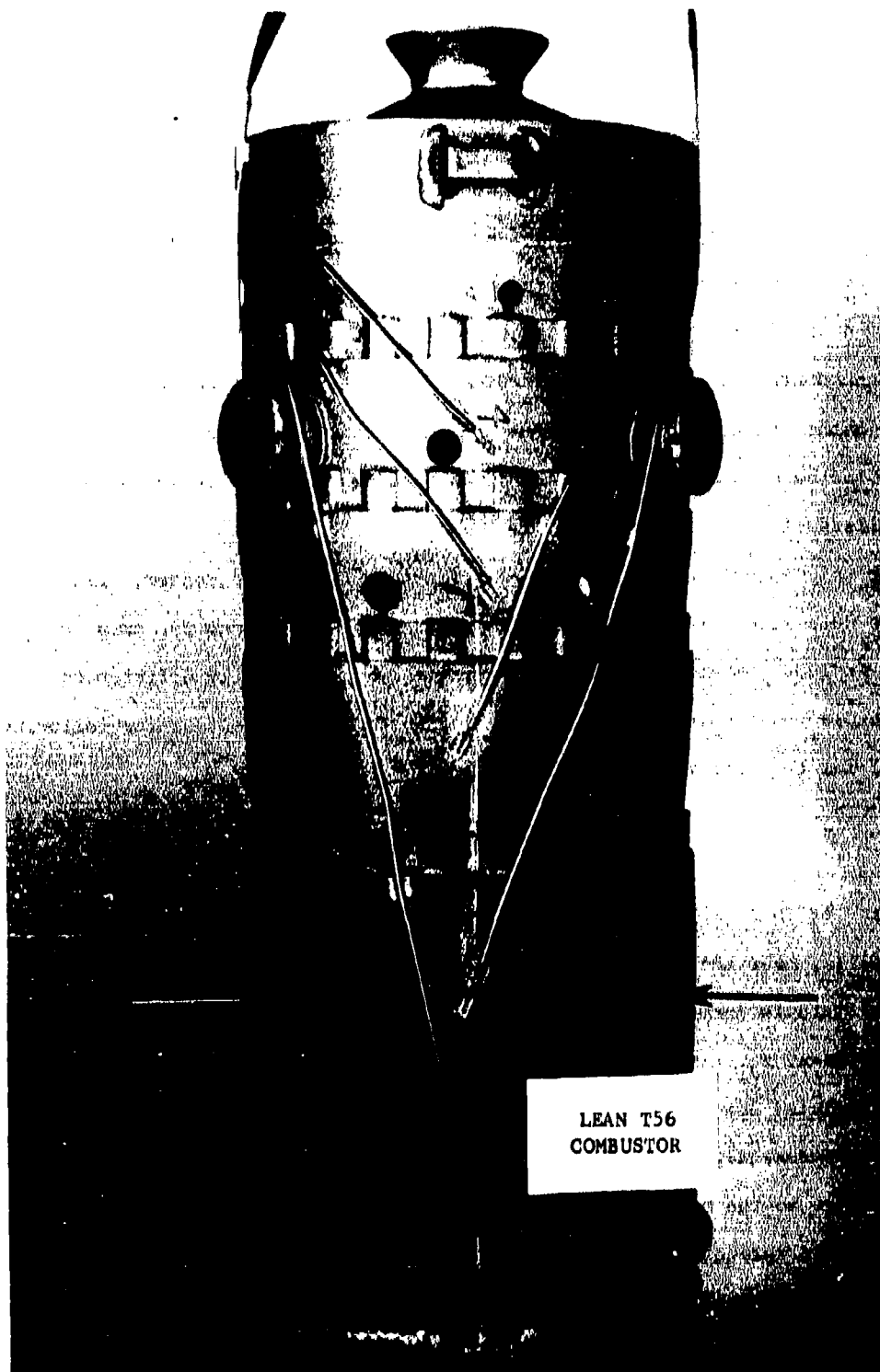


FIGURE 4. MODIFIED T56 COMBUSTOR  
NOTE: Arrows Point to Modified Dilution Holes



## SECTION III

## RESULTS

Investigation of Hydrogen Content Variations

The more luminous flame, produced as fuel hydrogen content is decreased, was found to substantially increase combustor liner temperature at all conditions studied. Data shown in Figure 5 for the high pressure cruise condition using baseline JP-4 and fuels A, B, and C are typical. Each incremental decrease in fuel hydrogen content results in a significant combustor liner temperature increase. Rather than present this type of data for all conditions and for all test fuels in the main body of the report, an appendix has been included which compiles all results.

During this investigation, a number of T56 combustors were tested. Liner temperature data were not repeatable between combustors. Reasons for this difficulty include combustor production variations and especially differences in thermocouple positioning. This finding led to the development of the following non-dimensional temperature parameter:

$$\frac{T_L - T_{LO}}{T_{LO} - T_3}$$

The numerator of this expression represents the increase in combustor liner temperature,  $T_L$ , over that obtained using the baseline fuel (14.5% hydrogen JP-4),  $T_{LO}$ . This is normalized by the difference between  $T_{LO}$  and combustor inlet temperature,  $T_3$ . It was found that data obtained using different combustors could be correlated using this parameter. It should also be noted that the parameter is representative of the fractional increase (over the baseline fuel) in heat transfer to the combustor liner.

## Initial JP-4/Xylene Fuel Blends (Fuels A-C):

Results for both idle and subsonic cruise conditions are shown in Figure 6 for the JP-4/Xylene blends, test fuels A, B, and C. In preparing these

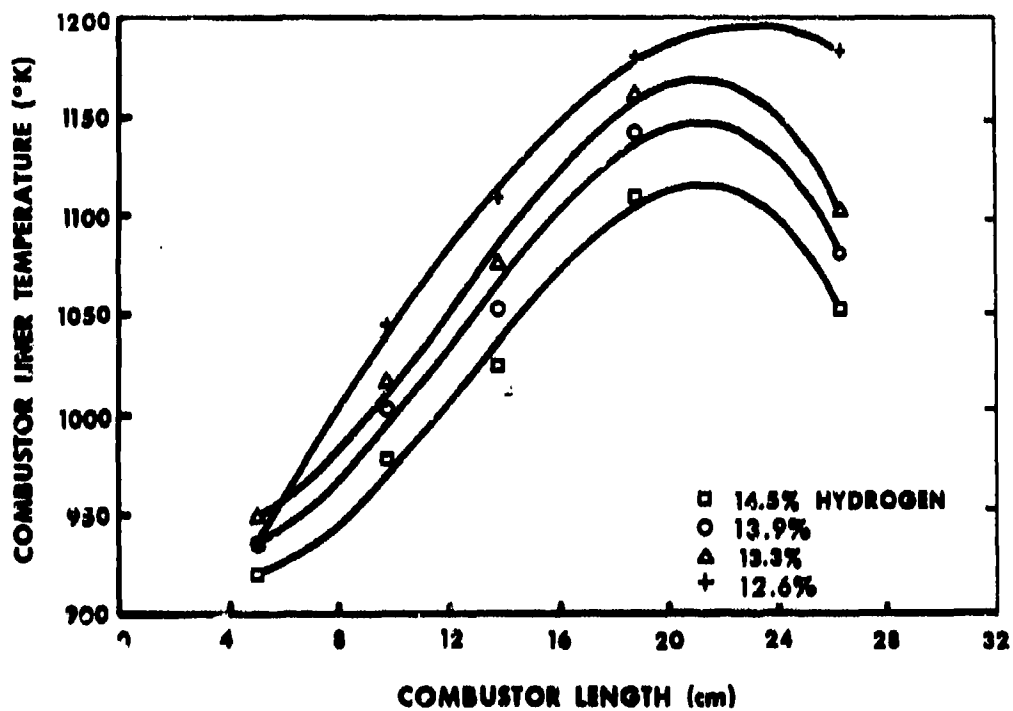


FIGURE 5. Combustor Liner Temperature Results at High-Pressure Ratio Cruise Condition.

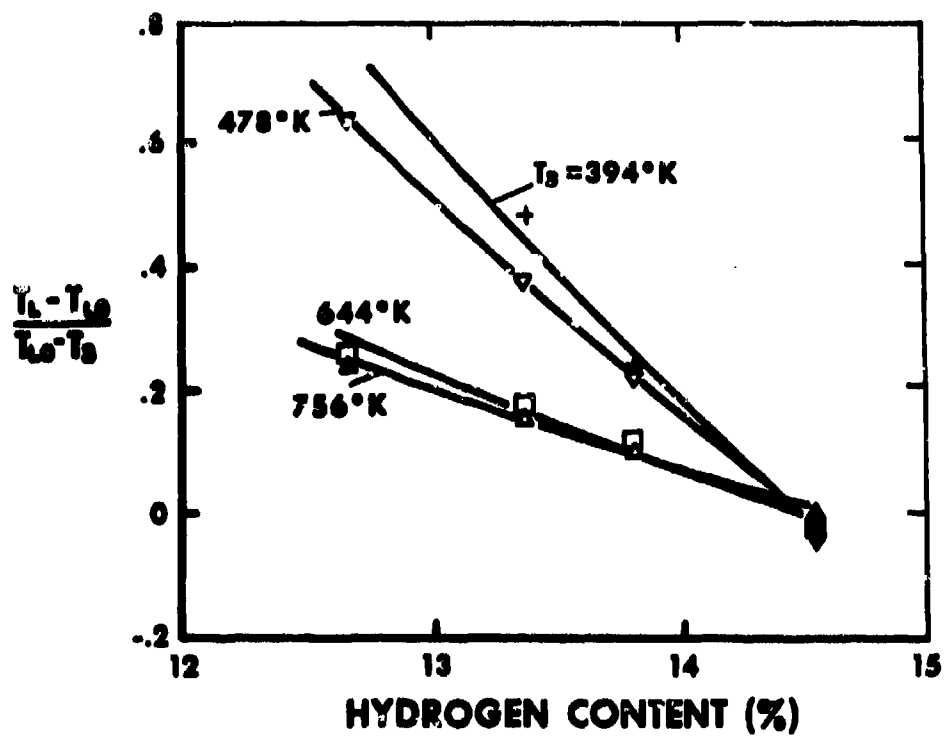


FIGURE 6. Dependence of Non-Dimensional Temperature Parameter on Hydrogen Content (JP-4/Xylene Blends).

results, thermocouple data from the mid-three combustor panels (which are thought to be most representative of important radiative effects) were averaged. While the idle results appear to be much more sensitive to hydrogen content, the combustion environment at these conditions is not severe and actual liner temperatures are relatively low. A more significant finding is that low and high pressure cruise results have surprisingly similar correlations. Data obtained during this testing are included in Tables A-1 through A-4.

Exhaust smoke also increased with decreased fuel hydrogen content as shown in Figure 7. Trends between smoke emission and hydrogen content are similar for each combustion condition. Increased absolute smoke emission between the 394°K and 644°K conditions is attributable to increased pressure and fuel-air ratio. Although a further small increase might be expected for the 756°K condition because of higher pressure, the lower fuel-air ratio required to maintain the 1200°K exhaust temperature (a limitation of the facility) results in a lower absolute smoke emission.

Gaseous emissions were not significantly affected by the changes to fuel hydrogen content. These data are indicated in Tables A-3 and A-4.

#### Full Range of Hydrogen Content Fuels (Fuels A-C and J-P):

Information relating to the expanded range of fuel hydrogen content includes results from testing of fuels J thru P in Phase II as well as fuels A thru C in Phase I. As in previous testing, it was intended that thermocouple data from the mid-three combustor liner panels would be used to determine the temperature parameter. However, the thermocouples on the center panel failed during testing and it was necessary to calculate the non-dimensional temperature parameter from the other two panels only. Nevertheless, because of the ability

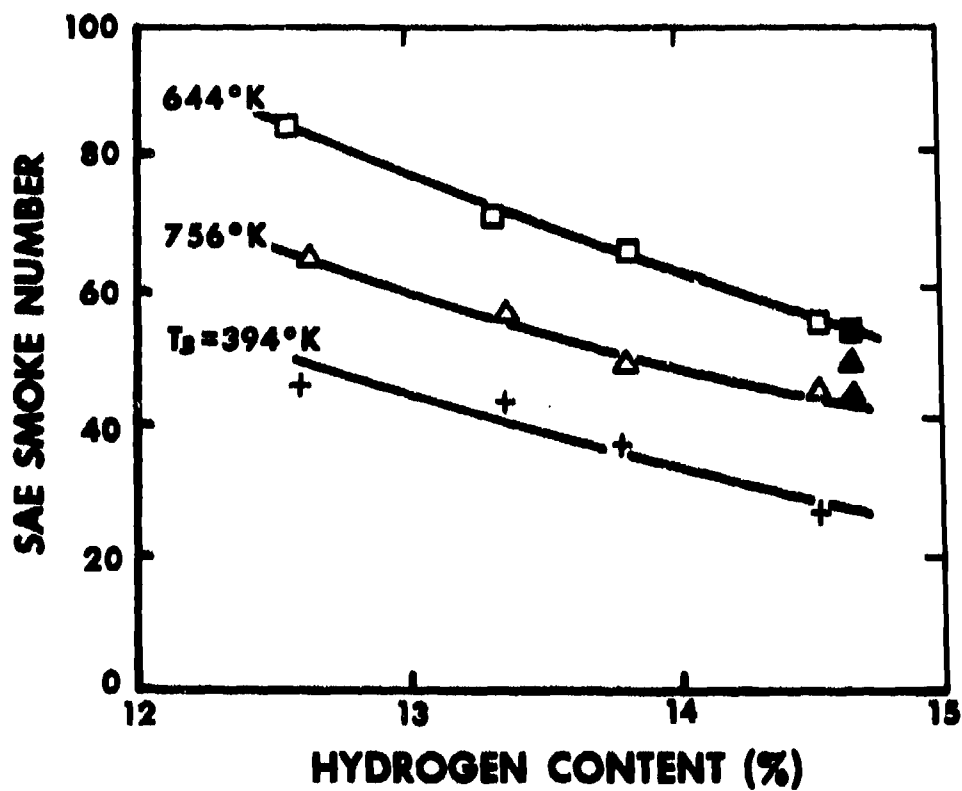


FIGURE 7. Smoke Emission Dependence on Hydrogen Content (JP-4/Xylene Blends).

of the non-dimensional temperature parameter to eliminate sensitivity to thermocouple location, it is believed that the comparisons based on this more limited amount of data remain valid.

These results have been plotted in Figure 8. The correlation established in preliminary testing with the JP-4/xylene blends (Fuels A-C) has been plotted for comparison and evaluation of reproducibility which appears to be excellent. The overall correlation acquired using all data has been fit by least squared analysis to an equation of the form:

$$T.P. = C_0 + C_1 \cdot (H) + C_2 \cdot (H)^2 \quad (1)$$

Where T.P. = Non-dimensional temperature parameter

H = Weight percent of hydrogen in the fuel

$C_0, C_1, C_2$  = Constants

The expected variation in radiative heat transfer due to changes in emissivity resulting from changes in primary zone carbon particle formation might be expected to follow an exponential relationship of the form:

$$\text{Radiative Heat Transfer} = C_3 [1 - \text{EXP} (C_4(H_0 - H))] \quad (2)$$

Where H = weight percent of hydrogen of the test fuel

$H_0 = 14.5$ , weight percent of hydrogen of the baseline JP-4 fuel

$C_3, C_4$  = Constants

In its expanded form, this second equation is simply a power series with constant coefficients. As such, a second order correlation (Equation 1) is an approximation which is consistent with physical phenomena. An attempt to evaluate the constants in the exponential function (Equation 2) based on the second order curve fit of the data was not satisfactory. The data scatter is probably responsible for this difficulty but as yet this explanation is unverified. Consequently, the results, while consistent with radiative heat transfer theory do not prove the direct applicability of Equation 2.

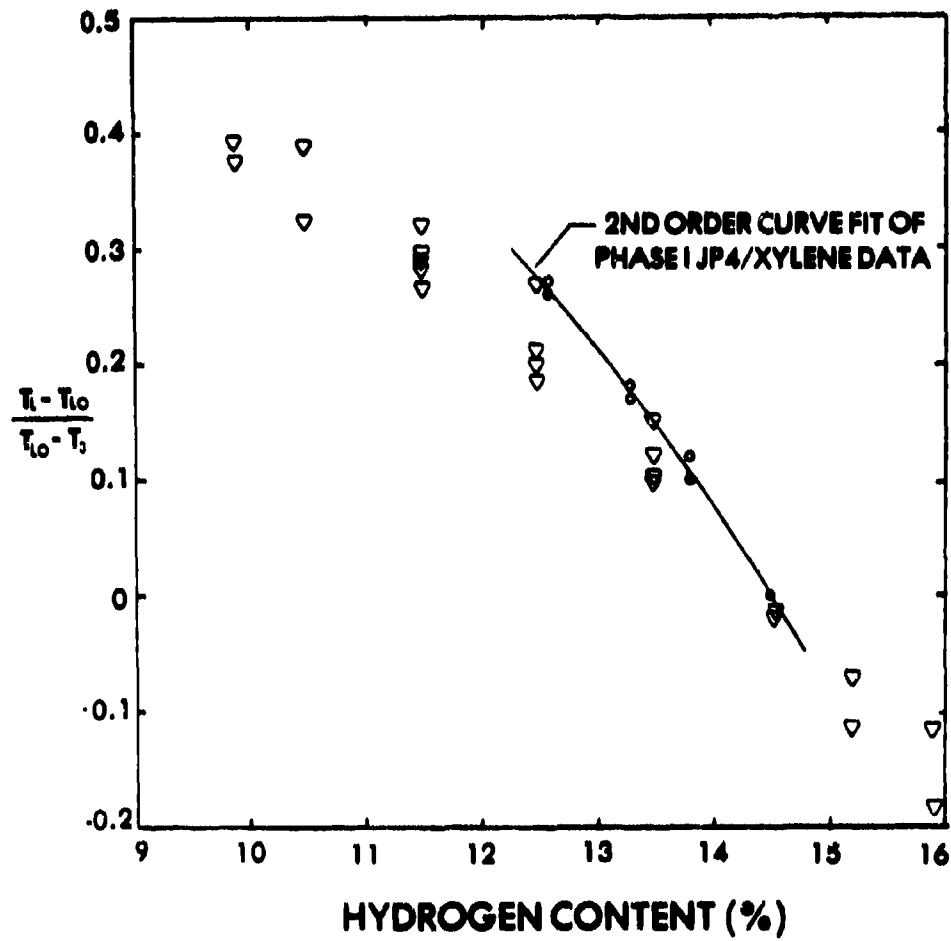


FIGURE 8. Dependence of Non-Dimensional Temperature Parameter on Hydrogen Content (Full Hydrogen Content Range).

Based on the JP-4/xylene blends and the JP-4/isooctane blends, the following second order relationship has been derived:

$$\text{TEMPERATURE PARAMETER} = -0.142 + 0.145H - 0.009H^2 \quad * (1a)$$

This correlation and the data from which it has been derived is plotted in Figure 9. The data are also tabulated in Tables A4 and A8.

#### JP-5/Xylene Blends (Fuels D-F):

Fuels D-F were studied at the two subsonic cruise conditions to determine the effect of fuel volatility on combustion liner temperature and smoke. Again, thermocouple data from the mid-three combustion panels have been used to calculate the nondimensional temperature parameter. It should be noted that the combustor used in these tests was not the same hardware as that used in the JP-4/xylene tests. The combustors were identical models, however, and any variations between them would be due to production variations, not design variations. It is believed that any such variations would be normalized by the nondimensional temperature parameter.

Figure 10 illustrates temperature parameter information for Fuels D-F along with the correlation previously established for JP-4. Differences between the JP-4 and JP-5 blend results indicate a definite effect of volatility. However, the figure also shows that the volatility effect is secondary to the effect of the fuel hydrogen content. Combustor liner temperature data for the JP-4/xylene blend testing are compiled in Table A6.

\* Several papers have resulted from this Technical Report prior to October 1977. In each case, the following equation has been sighted as the second order correlation of the Temperature Parameter with Hydrogen Content:  $T.P. = 0.098 + 0.138H - 0.009H^2$ . This equation was based on some data from Phase I which was obtained from plots of the data in lieu of the recorded data which had been misplaced. Before final editing of this TR, the recorded data was found and the correlation was adjusted to the values which appear in the text. Both equations correlate the data well. The adjustment that has been made to the coefficients is not considered significant.



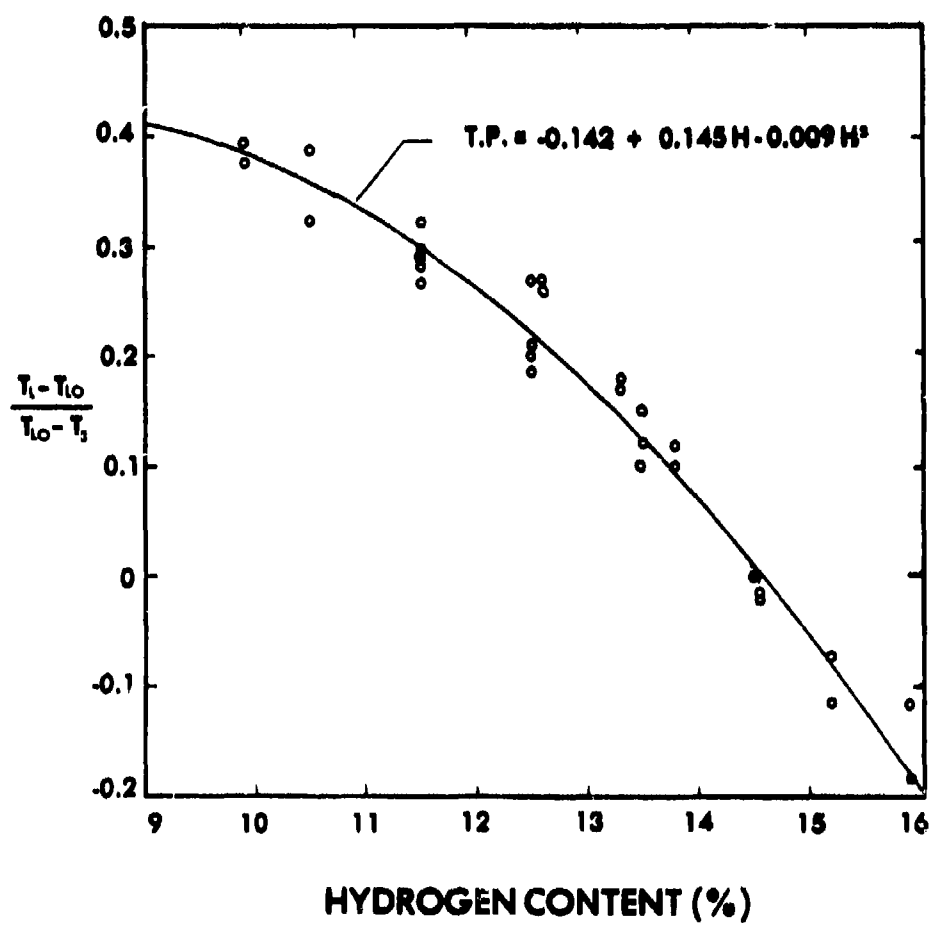


FIGURE 9. Correlation Equation for Non-Dimensional Temperature Parameter.

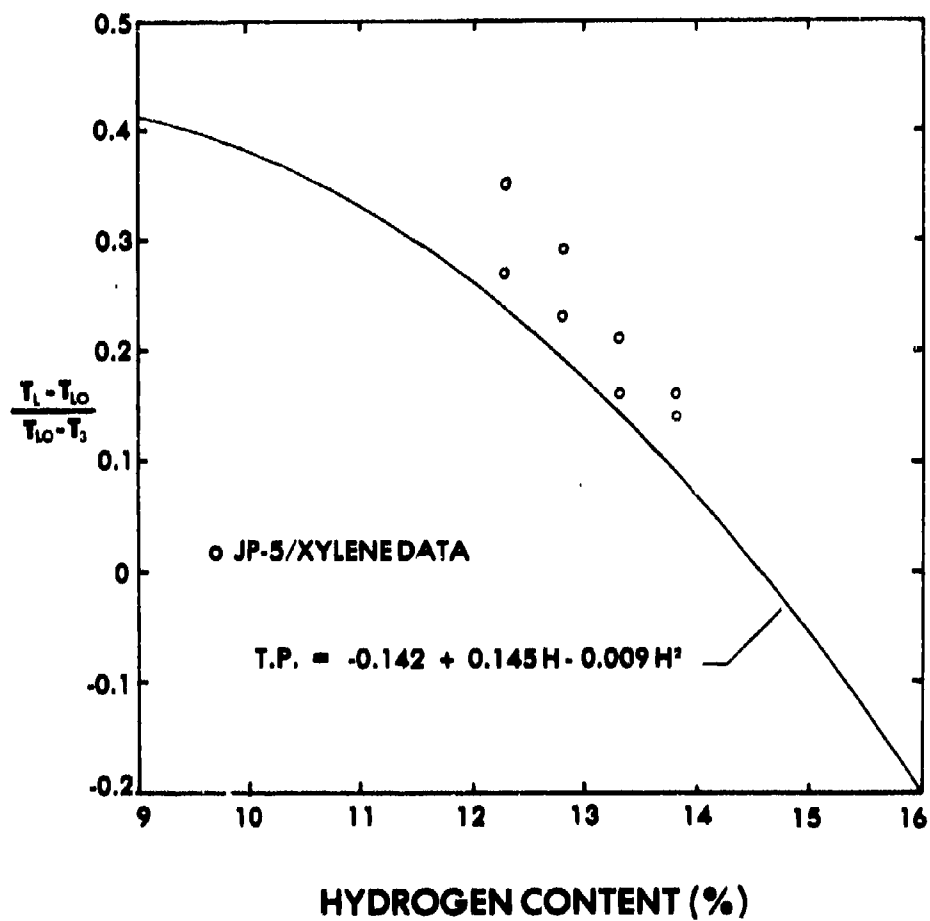


FIGURE 10. Comparison of JP-5/Blend Results with JP-4/Blend Results--Combustor Liner Temperature.

Exhaust smoke again increased with decreasing fuel hydrogen content (Figure 11). Absolute levels in the case of testing with JP-5 are generally similar to those found using JP-4 blends. As in the case of the JP-4 blends, gaseous emissions were not affected by hydrogen content variations among the JP-5/xylene blends. Data for this testing are included in Tables A5 and A6.

#### Effect of Hydrocarbon Type (Fuels G-I and Q-S):

The results of testing fuels of lower hydrogen content obtained in a manner other than blending xylene with JP-4 can be used to examine the universality of the correlation discussed above. Fuels G, H, and Q-S contain varying amounts of other hydrocarbon types as blending agents. Figure 12 compares the non-dimensional temperature parameter for each of these fuels with the correlation previously discussed. In each case, the results conform reasonably well to the correlation. It should be noted that Fuel R, having a large naphthalene component, was very sensitive to temperature. The results for this fuel shown in Figure 12, are from a test series run in the Summer months. An attempt was made to rerun this fuel in the Autumn. The attempt was unsuccessful due to severe amounts of solid deposits in the fuel (naphthalene dropping out of solution). If this were also happening to a lesser degree during the tests run in the Summer, then the hydrogen content of the liquid solution would actually be higher than anticipated (higher than 12.5%). The effect of this situation on Figure 12 is that the two data points representing Fuel R would actually move closer to the second order correlation. The only non-petroleum fuel tested was the Jet A derived from Canadian tar sands resources, Fuel I. Again, the temperature parameter is in close agreement with the correlation established previously (i.e., Figure 12). Data for this testing are included in Tables A7 and A9. All of these results indicate the dominant influence of hydrogen content on combustion zone radiation.

#### Fuel Bound Nitrogen Investigation

The effect of increased fuel bound nitrogen was evaluated by determining the additional  $\text{NO}_x$  emission occurring when nitrogen is present in the fuel and calculating

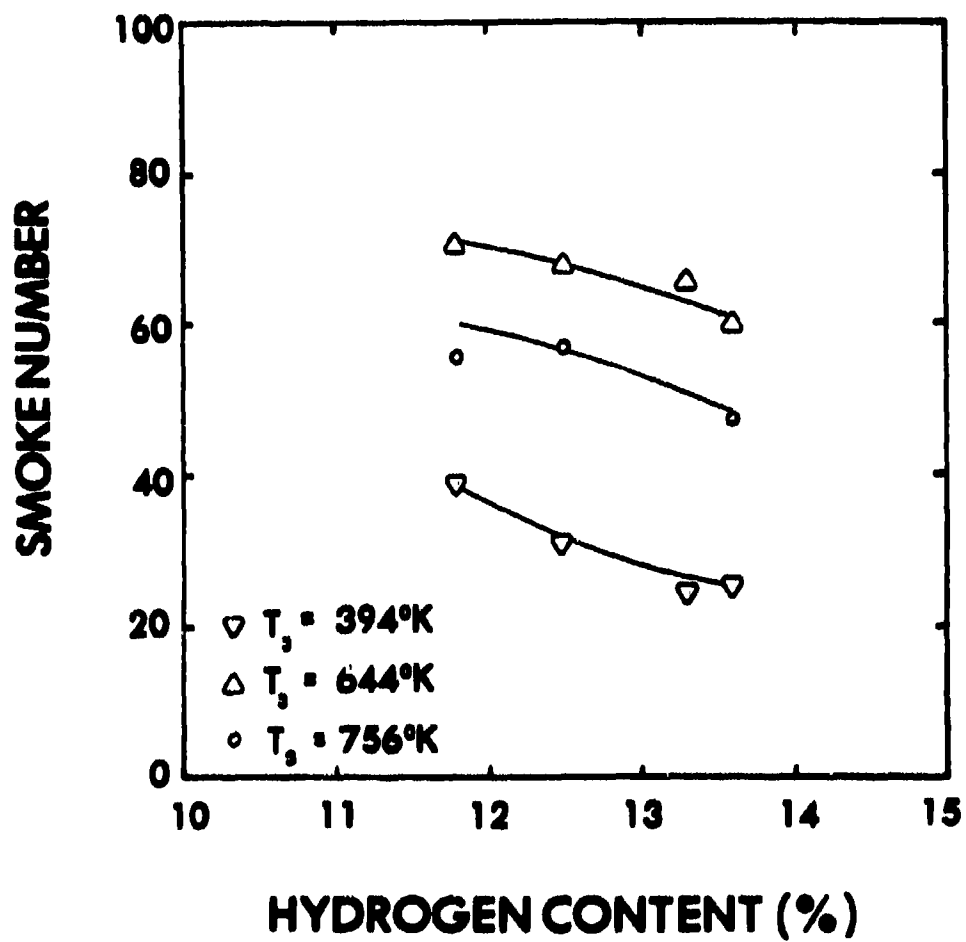


FIGURE 11. Smoke Emission for JP-5/Xylene Blends.

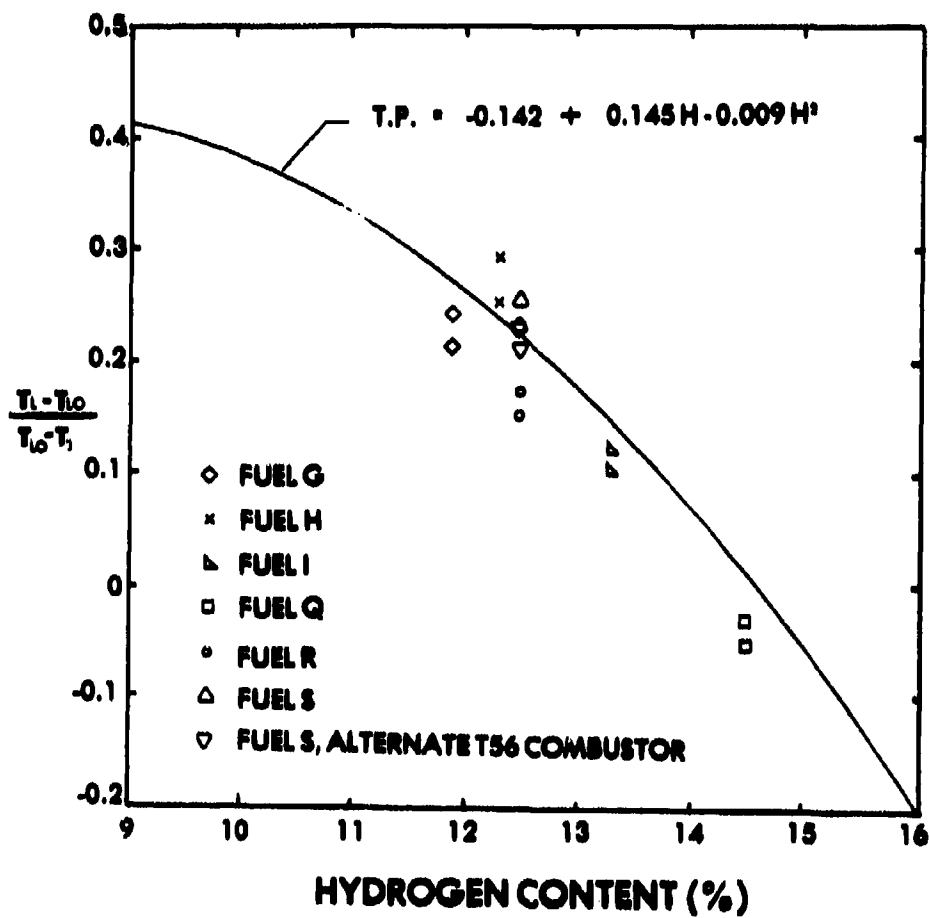


FIGURE 12. Effect of Hydrocarbon Type on Combustor Liner Temperature Correlation.

the percent of fuel nitrogen conversion to  $\text{NO}_x$  necessary to cause this increase. The baseline petroleum fuels used in this study had near zero ( $\approx 30$  ppmw) fuel nitrogen. Results presented in Figure 13 indicate the importance of two variables. First, as combustor inlet temperature is increased, conversion is reduced. Second, as fuel nitrogen concentrations are increased, conversion decreases. This second trend is consistent with previous results for an oil shale JP-4 derived sample with 0.025% nitrogen (12) which indicated near 100% conversion. The synfuel results are shown as a band in Figure 13 because of difficulties in accurately measuring small  $\text{NO}_x$  increases. Data used in developing the correlation in Figure 13 are listed in Tables A10 and A11.

#### Fuel Additive Testing

The anticipated result of significant smoke reduction by CI-2 was realized as shown in Table 6. For either the low pressure or high pressure cruise condition, a CI-2 concentration of 50 ppmw will reduce the smoke emissions of the JP-4/35% aromatic fuel to approximately the smoke emission occurring with the baseline JP-4. It was also observed that a higher concentration of CI-2 (100 and 300 ppmw) does not necessarily further reduce the smoke emissions levels. In fact, in some cases, increases beyond 50 ppmw had a detrimental effect on smoke emission.

Another area of interest was the effect of CI-2 on the combustor liner temperatures. Results shown in Table 7 indicate the impact of additive concentration on the average temperature of the mid-three combustor liner panels. In the case of the JP-4 baseline fuel, the results clearly indicate a near insensitivity to CI-2 concentration in the fuel. This observation is valid for low as well as high pressure cruise conditions. Similar results were found in the case of the JP-4/35% aromatic fuel, as shown in Table 7.

The relative insensitivity of combustor liner temperature to CI-2 concentration and the dramatic reduction in smoke emission afforded by the use of CI-2 are similar results to those of Reference 8. From this information, the mechanism by which the CI-2 works in the combustor can be hypothesized as acting to promote the secondary zone carbon consumption processes while not affecting the primary zone carbon particle formation reactions.

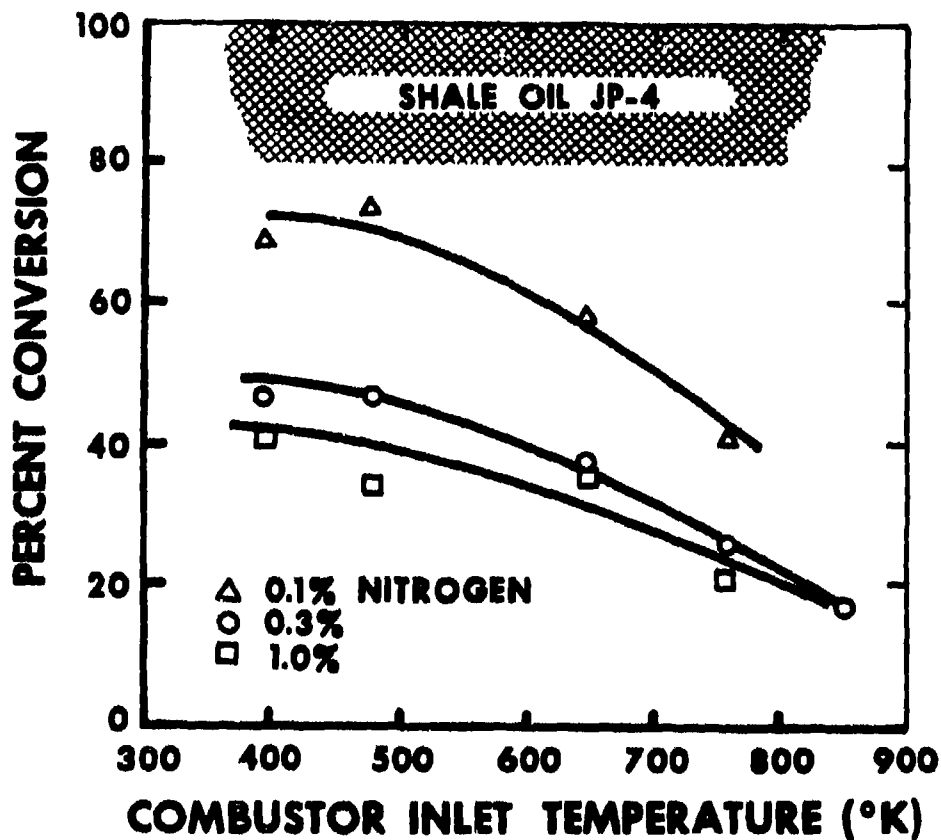


FIGURE 13. Fuel Bound Nitrogen Conversion to  $\text{NO}_x$  In An Aircraft Gas Turbine Combustor.

NOTE: Results apply only to the shale oil derived JP-4 evaluated. In large scale refining of jet fuel from shale oil high fuel bound nitrogen in the final product is not anticipated.

Table 6. EFFECT OF C1-2 ON SMOKE EMISSION

	JP-4			FUEL B		
	PPM Mn ADDED			PPM Mn ADDED		
	0	50	300	0	50	300
L. P. CRUISE	60.5	32.6	40	70	39.2	51.4
H. P. CRUISE	49.3	24.5	24	59	18.6	12



Table 7. EFFECT OF CI-2 ON LINER TEMPERATURE

## AVE TEMPERATURE OF MID-3 LINER PANELS (°K)

	L. P. CRUISE ( $T_3 = 644^\circ\text{K}$ )	H. P. CRUISE ( $T_3 = 756^\circ\text{K}$ )
JP-4	899	963
JP-4 + 50 ppmw Mn	892	957
JP-4 + 100 ppmw Mn	894	950
JP-4 + 300 ppmw Mn	894	955
JP-4/35% A	944	1022
JP-4/35% A + 50 ppmw Mn	916	994
JP-4/35% A + 100 ppmw Mn	922	995
JP-4/35% A + 300 ppmw Mn	928	999

Table 8 shows the effect of CI-2 on  $\text{NO}_x$  emissions for JP-4 and for JP-4/35% aromatics/.3% nitrogen. In addition to data for low and high power cruise conditions, a high mach cruise condition ( $T_3 = 838^\circ\text{K}$ ) is also presented. The JP-4 data is in agreement with the aforementioned previous AFAPL work in that a small reduction of  $\text{NO}_x$  was observed. The decrease of approximately 5% in  $\text{NO}_x$  indicates that the CI-2 is not significantly more effective at the high temperature conditions tested in this work. It is noted that the accuracy of these differences is not good because of measurement difficulties, although the trends are reliable. Very similar results were obtained with the high nitrogen fuel indicating that the additive also had a small effect on bound nitrogen conversion. Overall, the use of CI-2 does not represent a feasible method of  $\text{NO}_x$  control.

#### Lean Combustor Tests

The results of the lean combustor tests are shown in Table 9. Decreases in combustor liner temperatures obtained while using Fuel C range from  $100^\circ\text{K}$  at low pressure idle to  $135^\circ\text{K}$  for the same fuel at high pressure cruise. Of particular note is the fact that the lean combustor reduced the liner temperatures of the low hydrogen content fuels to less than that resulting from the use of JP-4 in a conventional combustor. This is true for each power condition.

The smoke emissions for the lean design did not differ significantly from standard combustor smoke emissions. This suggests that the reduced temperatures were due to reduced primary zone flame temperature rather than reduced particulate concentration. In addition, such a change can result in decreases in combustion stability and ignition difficulties. Consequently, these results must be very cautiously regarded.

Table 8. EFFECT OF CI-2 ON NOx EMISSION

	JP-4 BASE FUEL			FUEL B BASE		
	0	50	PPM Mn ADDED 100	300	0	PPM Mn ADDED 50 100 300 Fuel B-4 Fuel B-5 Fuel B-6
L. P. CRUISE ( $T_3 = 644^\circ\text{K}$ )	12.4	11.1	11.0	10.8	14.8	14.6 14.6 14.3
H. P. CRUISE ( $T_3 = 756^\circ\text{K}$ )	20.4	20.0	20.0	19.9	21.1	20.75 20.8 20.5
H. M. CRUISE ( $T_3 = 838^\circ\text{K}$ )	22.2	22.2	22.1	21.5		

Table 9. EFFECT OF LEAN COMBUSTOR ON LINER TEMPERATURE

AV. TEMPERATURE OF MID-3 LINER PANELS (°K)  
(STD. COMBUSTOR/LEAN COMBUSTOR)

	JP-4	FUEL A	FUEL B	FUEL C
L. P. IDLE	488/473	510/454	534/463	574/473
H. P. IDLE	623/567	656/573	681/588	719/601
L. P. CRUISE	911/810	943/842	958/857	982/869
H. P. CRUISE	1037/924	1066/945	1085/963	1110/974

## SECTION IV

## DISCUSSION

Combustor Liner Temperature Effects

The combustor liner temperature relationship presented in Figure 9 provides interesting information for further discussion. Combustor radiation results from non-luminous  $\text{CO}_2$  and  $\text{H}_2\text{O}$  infrared emission as well as blackbody emission from carbon particles. Under idle conditions, both fuel-air ratio and combustor pressure are lowest, resulting in minimum  $\text{CO}_2$  and  $\text{H}_2\text{O}$  concentration (moles/cc). Since the non-luminous radiation is lowest at these conditions, relative combustor temperature increases due to increased carbon particle radiation are emphasized. The trend of the non-dimensional temperature parameter with hydrogen content should be most significant at the idle operating conditions as shown in Figure 6.

Positive results of the correlation in Figure 8 also lead to the application of the new temperature parameter to other data. Results for the J79, JT8D, CJ805, and J57 engines (References 15-18) have been reanalyzed and plotted in Figure 14 along with the present correlation established using T56 data. These data, generally representative of cruise conditions with combustor inlet temperatures ranging from 547 to 756°K, present a good, consistent correlation. It should be noted, however, that each of these combustors involves a pressure atomizing fuel nozzle system and rich combustion zones. The limited data available for new designs involving airblast fuel injection and leaner combustion to preclude smoke formation indicate much less sensitivity of the non-dimensional temperature parameter to fuel hydrogen content. Figure 15 compares recent data for the CF6-50 combustor (10) with the rich combustor correlation. Low  $\text{NO}_x$  emission designs

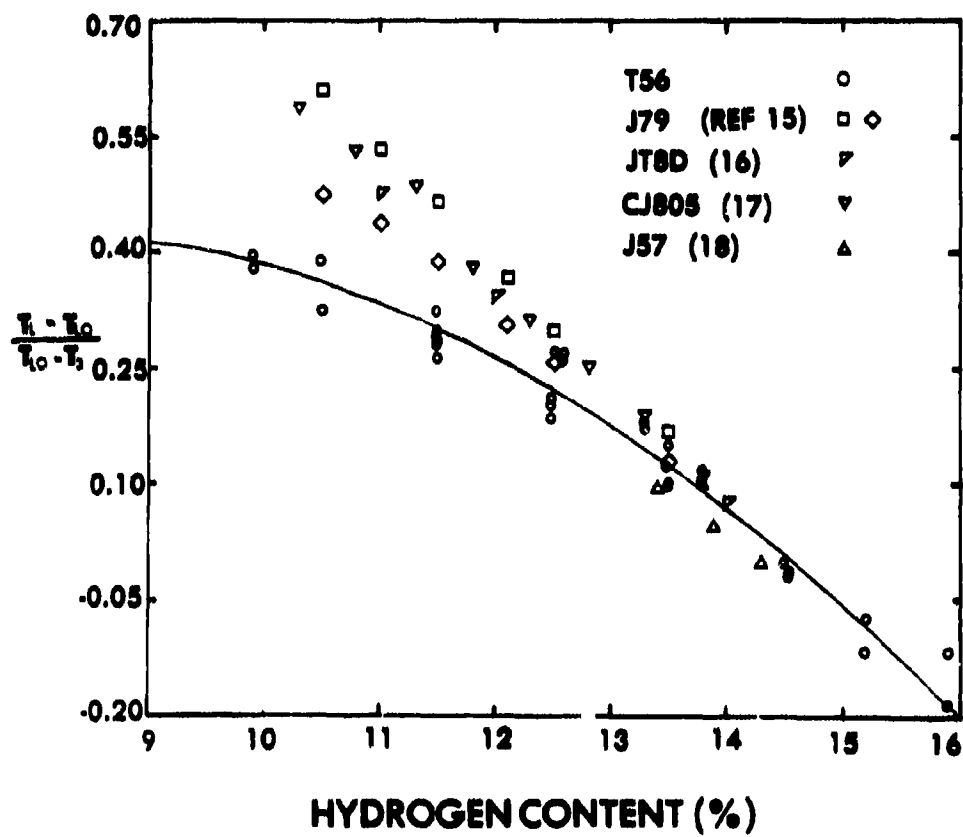


FIGURE 14. Liner Temperature Correlation for Many Combustor Types.

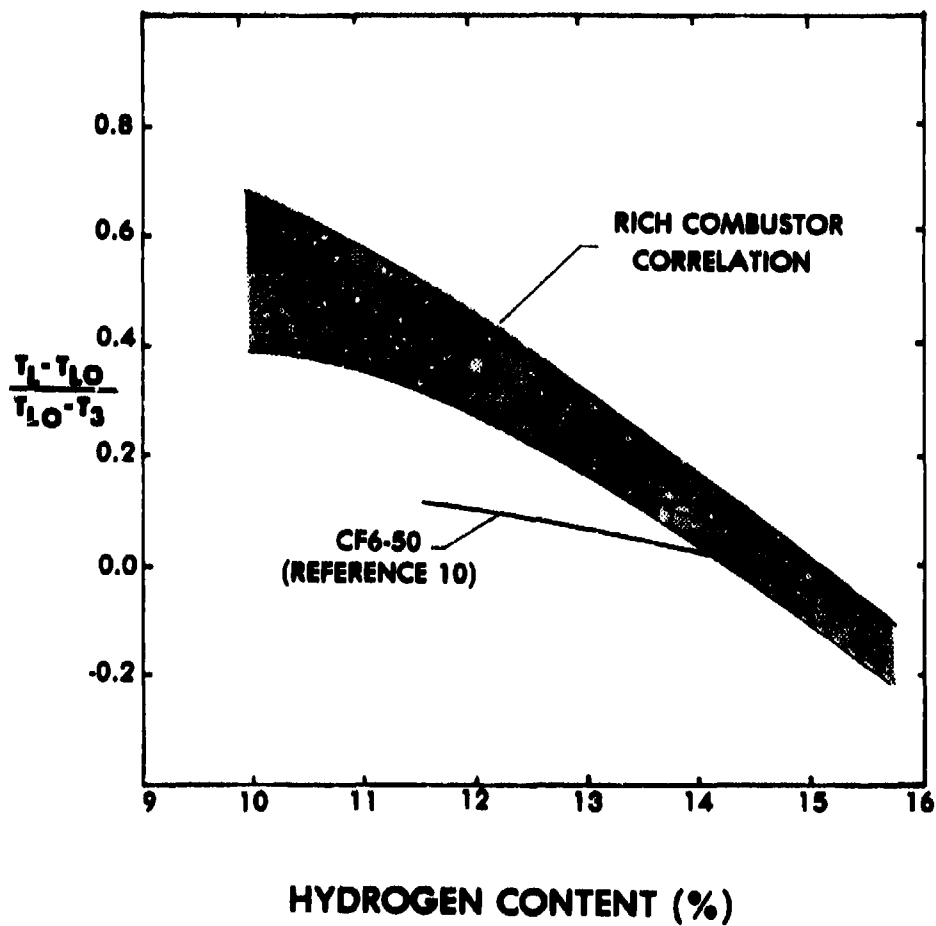


FIGURE 15: Comparison of CF6-50 Results with Rich Combustor Correlation.

investigated in References 10 and 11 indicate even less sensitivity to fuel type. Other new engine combustion systems with airblast atomization and leaner combustion for minimized smoke emission and higher pressure ratios should be examined.

#### Fuel Bound Nitrogen Effects

The results discussed in Section III-B provide an excellent assessment of the trends associated with fuel bound nitrogen in aircraft gas turbine combustors. The important points are: a) near 100% conversion is anticipated at the nitrogen content levels of interest ( $<0.1\%$ ), b) there is a trend to decreased conversion percentage with increasing nitrogen content, and c) increasing combustor inlet temperature also results in decreased conversion. This information is sufficient for many of the economic and environmental trade-offs and studies which will be necessary.

It should be recognized, however, that the nitrogen content levels discussed here may not at all be typical of future synfuels. The JP-4 and JP-5 produced from oil shale both contained less nitrogen than in the lowest level tested in this study even though no strong effort was made to reduce the nitrogen level in these oil shale fuels. It also appears that non-combustion related factors may determine the level of processing necessary, as both storage stability and thermal stability are detrimentally affected by high nitrogen levels.

#### Minimizing Combustion System Impact

The fuel additive approach briefly examined in this program would be regarded as feasible only if the combustion results are highly positive, as many problems are known to exist with the usage of such a material. For example, deposition of the metal in engine hot section (combustor and turbine) components, plugging



of nozzles and afterburner spray bars, and reduction in thermal stability have been observed. While significant reductions in smoke emission were noted, the data is conclusive in indicating no significant effect of the additive on the impact of reduced hydrogen content or combustor liner temperature. Consequently, this option is not being further pursued.

While the lean combustor study represented a relatively minor modification to the combustion system, true application of the lean combustor concept requires major redesign or initial design with a completely new engine system. Recent combustion system designs for instance have successfully utilized air blast fuel atomizers in conjunction with lean primary combustion zones to reduce both smoke and the combustor's sensitivity to fuel hydrogen content. Although the attempt in this program to attain lean combustion resulted in significantly reduced liner temperature, the acceptability of other combustor performance factors (especially pattern factor, ground and altitude ignition and stability) was not assessed. It is also noted that this modification did not significantly decrease smoke emission leading to the speculation that particulate formation processes were not affected--the liner temperature reductions are primarily a result of reduced primary zone temperature.

Additional programming required for more thorough examination of ways to minimize combustion system impacts is discussed below.

#### Other Required Information

In regard to main combustors, future studies must examine new combustor design concepts to overcome the problems which have been identified. Lean, low-smoke combustor systems will comprise a major approach to utilizing new fuels. The information base which has been developed from current research on staged combustion systems with lean main combustion zones for lower  $\text{NO}_x$  emission will contribute toward this development. In this case, fuel is premixed with air and pre-vaporized prior to entering the combustion zone. Better fundamental understanding of pre-ignition and flashback at practical combustor inlet conditions will be necessary for application of these techniques.

The impact of fuel characteristics on afterburner operation and performance must also be defined. Similar liner temperature problems, infrared plume signature, combustion efficiency, light-off transients, and combustion stability must be investigated. If problems are identified, studies to examine new design concepts analogous to those required for main burners may be necessary.

A number of fundamental research topics are equally important to progress in this area. Additional information is necessary concerning fuel hydrocarbon pyrolysis and particulate formation in lower hydrogen content fuels. Enhanced modeling effort to predict combustor radiant loading, smoke, ignition, stability, and afterburner plume infrared radiation may also be required. Other areas of importance include the improved relating of fuel test methods to behavior in the actual combustor and incorporation of durability models to interpret test results such as the combustor liner temperature data presented here.

## SECTION V

### CONCLUSIONS/SUMMARY

Anticipated changes in future crude sources are expected to have a significant impact on the trade-off between fuel processing costs and fuel quality. Technical efforts are required to define new fuel specifications with the intent of minimizing the total cost of system operation. Conclusions from the subject work which contribute to the technology base necessary for these future decisions are as follows:

(a) Reductions in fuel hydrogen content substantially increase combustor liner temperatures in systems equipped with conventional pressure-atomizing fuel nozzles utilizing rich combustion zones.

(b) A non-dimensional temperature parameter has been developed to minimize difficulties associated with thermocouple positioning and combustor production variations. Use of this parameter has also resulted in a good correlation of a wide variety of data involving rich combustion systems (J57, J79, CJ805, JT8D, T56). Comparison of recent CF6-50 combustor liner temperature data with the correlation indicated that newer designs with airblast fuel injection and leaner combustion may be much less sensitive to fuel hydrogen content.

(c) Testing with both JP-4 and JP-5 blend with xylene indicated that volatility has a noticeable effect on the correlations discussed above but that this effect is secondary to fuel hydrogen content.

(d) Testing of Jet A, JP-4, and Iso-Octane doped with a single-ring aromatic, naphthenes, and naphthalene produced results in agreement with the correlation obtained with the JP-4/xylene blends. A Jet A produced from Canadian tar sands which was high in aromatic content (low hydrogen content) also was in agreement with the xylene blend results.

(e) SAE Smoke Number was found to be substantially increased by lower hydrogen content for all fuels tested. Gaseous emissions (CO, HC, and NO<sub>x</sub>) were not affected by fuel hydrogen content variations between 12.7-14.5%.

(f) Fuel bound nitrogen conversion under practical aircraft combustor conditions (up to 838°K inlet temperature) was found to be dependent on both fuel nitrogen concentration and combustor inlet temperature.

(g) The use of a smoke abatement fuel additive was shown to effectively reduce smoke emission with a low hydrogen content fuel but has little effect on combustor liner temperature increases.

(h) Testing of a combustor modified to have a 28% leaner primary zone indicated significantly reduced (approximately 100°C) combustor liner temperatures, but had little effect on smoke emission.

Many recommendations for future work are indicated by these results. New engine types employing low smoke combustor designs must be tested. All of these results will require confirmation by engine testing. Once this information is in hand, technology development to allow application of new concepts intended to overcome difficulties caused by future fuels will be necessary. Lean, premix/prevaporized combustion systems are expected to be the principal approach for these future designs. Finally, combustion research is necessary to supply a large amount of fundamental information made necessary by the projected fuel changes. Areas of interest include the kinetics of hydrocarbon pyrolysis, particulate formation and radiative processes, and the possibility of employing some means of fuel reforming prior to the main combustion zone.

## APPENDIX

This section contains the test data which was used in making the plots included in the text of this report. This recorded data does not represent specific point measurements. Liner temperature readings are averages of several specific thermocouple readings. These averages are typically of several repeat points, of several measurements of a single liner panel, and/or of several liner panels used in the calculation of the temperature parameter. The legends of the tables or the text of the report indicate the source of the recorded data. Emissions measurements are also typically averages of several repeat test points.

## NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>
SN	Smoke Number (see Society of Automotive Engineers, Aerospace Recommended Practice 1179-SAE ARP 1179).
THC	Total Hydrocarbons, Emission Index*
NO <sub>x</sub>	Total Oxides of Nitrogen (NO and NO <sub>2</sub> ), Emission Index*
CO	Carbon Monoxide, Emission Index*
CI	Combustion Inefficiency (in percent)

\* Calculation procedure for these quantities can be found in SAE ARP 1256.

TABLE A-1. AVERAGE LINER TEMPERATURES AT EACH LINER PANEL FOR  
THE IDLE TEST CONDITIONS FOR BASELINE JP-4 AND XYLENE  
DOPED JP-4 FUELS, PHASE I.

Low Pressure Ratio Idle ( $T_3 = 394^\circ\text{K}$ )

Fuel Designation	Type	Average Liner Temperatures ( $^\circ\text{K}$ )				
		Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
JP-4	JP-4	474	484	490	494	436
A	JP-4/25% Aromatics	489	503	511	515	454
B	JP-4/35% Aromatics	513	530	540	532	467
C	JP-4/45% Aromatics	555	569	601	562	530

High Pressure Ratio Idle ( $T_3 = 478^\circ\text{K}$ )

Fuel Designation	Type	Average Liner Temperatures ( $^\circ\text{K}$ )				
		Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
JP-4	JP-4	614	616	626	625	557
A	JP-4/25% Aromatics	640	649	662	656	561
B	JP-4/35% Aromatics	635	670	684	678	561
C	JP-4/45% Aromatics	663	716	757	678	651

TABLE A-2. AVERAGE LINER TEMPERATURES AT EACH LINER PANEL FOR  
THE CRUISE TEST CONDITIONS FOR BASELINE JP-4 AND  
XYLENE DOPED JP-4 FUELS, PHASE I

Low Pressure Ratio Cruise (T3 = 644°K)

Fuel Designation	Type	AVERAGE LINER TEMPERATURES (°K)				
		Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
JP-4	JP-4	791	952	997	986	954
A	JP-4/25% Aromatics	801	978	930	1025	999
B	JP-4/35% Aromatics	808	889	944	1043	1008
C	JP-4/45% Aromatics	804	913	978	1055	1075

High Pressure Ratio Cruise (T3 = 755°K)

Fuel Designation	Type	AVERAGE LINER TEMPERATURES (°K)				
		Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
JP-4	JP-4	919	978	1025	1109	1054
A	JP-4/25% Aromatics	935	1004	1053	1141	1082
B	JP-4/35% Aromatics	949	1016	1076	1161	1103
C	JP-4/45% Aromatics	935	1045	1109	1180	1183

TABLE A-3. TEMPERATURE PARAMETER, GASEOUS EMISSIONS, AND SMOKE DATA  
FOR THE IDLE TEST CONDITIONS FOR BASELINE JP-4 AND XYLENE  
DOPED JP-4 FUELS, PHASE I.

Low Pressure Ratio Idle (T3 = 394°K)

<u>Fuel</u> <u>Designation</u>	<u>Type</u>	<u>Temperature</u> <u>Parameter</u>	<u>Gaseous Emissions and Smoke Data</u>			
			<u>SN</u>	<u>THC</u>	<u>NOx</u>	<u>CI</u>
JP-4	JP-4	0	25	28.0	2.3	43.0
A	JP-4/25% Aromatics	0.22	37	29.5	2.4	43.7
B	JP-4/35% Aromatics	0.47	43	28.0	2.4	43.1
C	JP-4/45% Aromatics	0.90	45	42.7	1.8	38.4
						5.21

High Pressure Ratio Idle (T3 = 478°K)

<u>Fuel</u> <u>Designation</u>	<u>Type</u>	<u>Temperature</u> <u>Parameter</u>	<u>Gaseous Emissions and Smoke Data</u>			
			<u>SN</u>	<u>THC</u>	<u>NOx</u>	<u>CI</u>
JP-4	JP-4	0	44	2.5	4.4	22.7
A	JP-4/25% Aromatics	0.23	58	2.9	4.1	22.6
B	JP-4/35% Aromatics	0.38	62	2.9	4.2	23.9
C	JP-4/45% Aromatics	0.65	64	6.1	3.4	24.8
						1.20



TABLE A-4. TEMPERATURE PARAMETER, GASEOUS EMISSIONS, AND SMOKE DATA FOR THE  
CRUISE TEST CONDITIONS FOR BASELINE JP-4 AND XYLENE DOPED JP-4  
FUELS, PHASE I.

Low Pressure Ratio Cruise (T3 = 644°K)

Fuel Designation	Type	Temperature Parameter	Gaseous Emissions and Smoke Data			
			SN	THC	NOx	CO CI
JP-4	JP-4	0	56		10.5	7.5
A	JP-4/25% Aromatics	0.12	65		10.1	7.5
B	JP-4/35% Aromatics	0.18	70		10.1	7.7
C	JP-4/45% Aromatics	0.27	85		9.5	11.6

High Pressure Ratio Cruise (T3 = 755°K)

Fuel Designation	Type	Temperature Parameter	Gaseous Emissions and Smoke Data			
			SN	THC	NOx	CO CI
JP-4	JP-4	0	48		17.7	7.4
A	JP-4/25% Aromatics	0.10	52		17.0	7.2
B	JP-4/35% Aromatics	0.17	59		17.5	7.3
C	JP-4/45% Aromatics	0.26	64		17.1	8.9

TABLE A-5. SMOKE AND NO<sub>x</sub> EMISSION DATA FOR THE IDLE TEST  
CONDITIONS FOR THE BASELINE JP-4, STANDARD JP-5,  
AND XYLENE DOPED JP-5 FUELS, PHASE I.

Low Pressure Ratio Idle (T3 = 394°K)

<u>Fuel</u>		<u>SN</u>	<u>NO<sub>x</sub> Emission</u>
<u>Designation</u>	<u>Type</u>		
JP-4	JP-4	16	2.46
JP-5	JP-5	25	2.33
D	JP-5/25% Aromatics	24	2.40
E	JP-5/35% Aromatics	31	2.30
F	JP-5/45% Aromatics	39	2.17

High Pressure Ratio Idle (T3 = 478°K)

<u>Fuel</u>		<u>SN</u>	<u>NO<sub>x</sub> Emission</u>
<u>Designation</u>	<u>Type</u>		
JP-4	JP-4	46	4.53
JP-5	JP-5	59	4.23
D	JP-5/25% Aromatics	60	4.27
E	JP-5/35% Aromatics	63	4.20
F	JP-5/45% Aromatics	58	4.17

TABLE A-6. AVERAGE LINER TEMPERATURE OF MID-THREE LINER PANELS, SMOKE, AND NOX EMISSION FOR THE CRUISE TEST CONDITIONS FOR THE BASELINE JP-4, STANDARD JP-5, AND XYLENE DOPED JP-5 FUELS, PHASE I.

Low Pressure Ratio Cruise (T3 = 644°K)

<u>Fuel Designation</u>	<u>Type</u>	<u>Liner Temperature (°K) (Average of Mid-Three Panels)</u>	<u>SM</u>	<u>NOx Emission</u>
JP-4	JP-4	790	60	13.60
JP-5	JP-5	814	60	13.30
D	JP-5/25% Aromatics	821	65	12.70
E	JP-5/35% Aromatics	833	68	12.60
F	JP-5/45% Aromatics	841	70	12.97

High Pressure Ratio Cruise (T3 = 755°K)

<u>Fuel Designation</u>	<u>Type</u>	<u>Liner Temperature (°K) (Average of Mid-Three Panels)</u>	<u>SN</u>	<u>NOx Emission</u>
JP-4	JP-4	880	49	20.83
JP-5	JP-5	897	48	19.80
D	JP-5/25% Aromatics	900	—	—
E	JP-5/35% Aromatics	909	57	19.75
F	JP-5/45% Aromatics	914	56	19.60

TABLE A-7. LINER TEMPERATURE DATA FOR ALL TEST CONDITIONS FOR HIGH AROMATIC,  
HIGH NAPHTHALENE, AND ALTERNATE SOURCE FUEL, PHASE I.

Fuel Designation	Type	Low Pressure Ratio Idle (T3 = 394°K)		High Pressure Ratio Idle (T3 = 478°K)	
		Liner Temp (°K)	Temp Parameter	Liner Temp (°K)	Temp Parameter
G	NASA/High Aromatic	509	0.21	683	0.42
H	NASA/High Naphthalene	527	0.39	706	0.57
I	Shell Canada Tar Sands	511	0.23	667	0.31

Fuel Designation	Type	Low Pressure Ratio Cruise (T3 = 644°K)		High Pressure Ratio Cruise (T3 = 755°K)	
		Liner Temp (°K)	Temp Parameter	Liner Temp (°K)	Temp Parameter
G	NASA/High Aromatic	975	0.24	1098	0.21
H	NASA/High Naphthalene	990	0.29	1109	0.25
I	Shell Canada Tar Sands	938	0.10	1071	0.12

TABLE A-8. LINER TEMPERATURE DATA FOR CRUISE TEST CONDITIONS FOR EXPANDED HYDROGEN CONTENT FUELS, PHASE II.

Fuel Designation	Type	Low Pressure Ratio Cruise (T3 = 644°K)		High Pressure Ratio Cruise (T3 = 755°K)	
		Liner Temp (°K)	Temp Parameter	Liner Temp (°K)	Temp Parameter
J	Xylene	899	0.39	965	0.38
K	JP-4/Xylene	899	0.39	957	0.32
L	JP-4/Xylene	896	0.32	948	0.27
		875	0.29	953	0.30
		983*	0.28*	1056*	0.29*
M	JP-4/Xylene	871	0.27	940	0.21
		962*	0.19*	1035*	0.20*
N	JP-4/Xylene	850	0.15	926	0.12
		939*	0.10*	1012*	0.10*
O	JP-4/Iso-Octane	823	-0.11	904	-0.07
P	Iso-Octane	809	-0.18	897	-0.12

\* Alternate T56 Can Used

TABLE A-9. LINER TEMPERATURE DATA FOR CRUISE TEST CONDITIONS FOR  
FUELS BLENDED USING DIFFERENT HYDROCARBONS TO ALTER FUEL  
HYDROGEN CONTENT, PHASE II.

Fuel Designation	Type	Low Pressure Ratio Cruise (T3 = 644°K)		High Pressure Ratio Cruise (T3 = 755°K)	
		Liner Temperature (°K)	Temp Parameter	Liner Temperature (°K)	Temp Parameter
Q	Iso-Octane/Decalin	835	-0.05	911	-0.03
R	JP-4/Napthalene/ Xylene	879	0.17	939	0.15
S	JP-4/Tetralin	868 973*	0.25 0.23	942 1031*	0.23 0.21

\* Alternate T56 Can Used

TABLE A-10. Smoke and Gaseous Emissions Data for the Idle Test Conditions for Nitrogen Doped Fuels, Phase I

EMISSIONS INDEX						
L.P. IDLE ( $T_3=394^\circ\text{K}$ )						
<u>FUEL</u> <u>DESIGNATION</u>	<u>TYPE</u>	<u>SN</u>	<u>THC</u>	<u>NOx</u>	<u>CO</u>	<u>CI</u>
T	1.0% NITROGEN	34	37.6	10.9	40.8	4.64
U	0.3% NITROGEN	34	40.0	5.3	38.4	4.90
V	0.1% NITROGEN	NA	57.1	3.1	44.9	6.80
H.P. IDLE ( $T_3=478^\circ\text{K}$ )						
T	1.0% NITROGEN	47	6.0	11.8	21.3	1.10
U	0.3% NITROGEN	53	5.5	7.4	20.9	1.04
V	0.1% NITROGEN	43	6.5	5.3	28.7	1.32

TABLE A-11. NOx and CO Emission Data for the Cruise Test Conditions for Nitrogen Doped Fuels, Phase I

<u>FUEL</u>		<u>EMISSIONS INDEX</u>				
		<u>SN</u>	<u>THC</u>	<u>NOx</u>	<u>CO</u>	<u>CI</u>
<u>L.P. Cruise (T<sub>3</sub> = 644°K)</u>						
<u>DESIGNATION</u>	<u>TYPE</u>					
T	1.0% NITROGEN	NA		17.9	10.4	
U	0.3% NITROGEN			12.5	9.7	
V	0.1% NITROGEN			11.3	7.4	
<u>H.P. Cruise (T<sub>3</sub> = 755°K)</u>						
T	1.0% NITROGEN			20.5	9.7	
U	0.3% NITROGEN			18.7	8.3	
V	0.1% NITROGEN			17.9	7.9	



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